The Trouble with Neutrinos

Dan Dwyer - Berkeley Lab

Sambamurti Memorial Lecture
June 26, 2012

Today's Journey

The Trouble with Neutrinos:
A story in 4 acts.

Act 1:
The troublesome origin of neutrinos

Act 2:
Neutrino experiments, great and not so great

Act 3:
Neutrino Oscillation and The Daya Bay Experiment

Act 4:
More trouble on the horizon...

Act 1:
The troublesome origin of neutrinos

Who needs Neutrinos?

Make money?

Improve fuel efficiency?

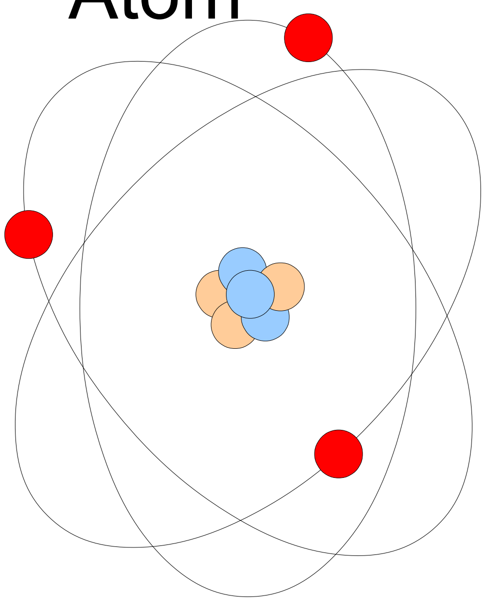
World Peace?

No, neutrinos don't do any of those things...

A little nuclear refresher...

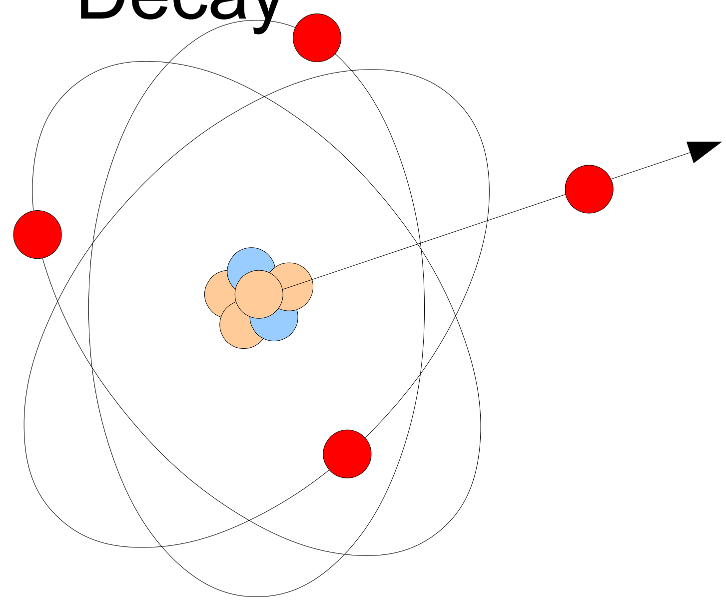
Early models of the atom

'Classic' Atom



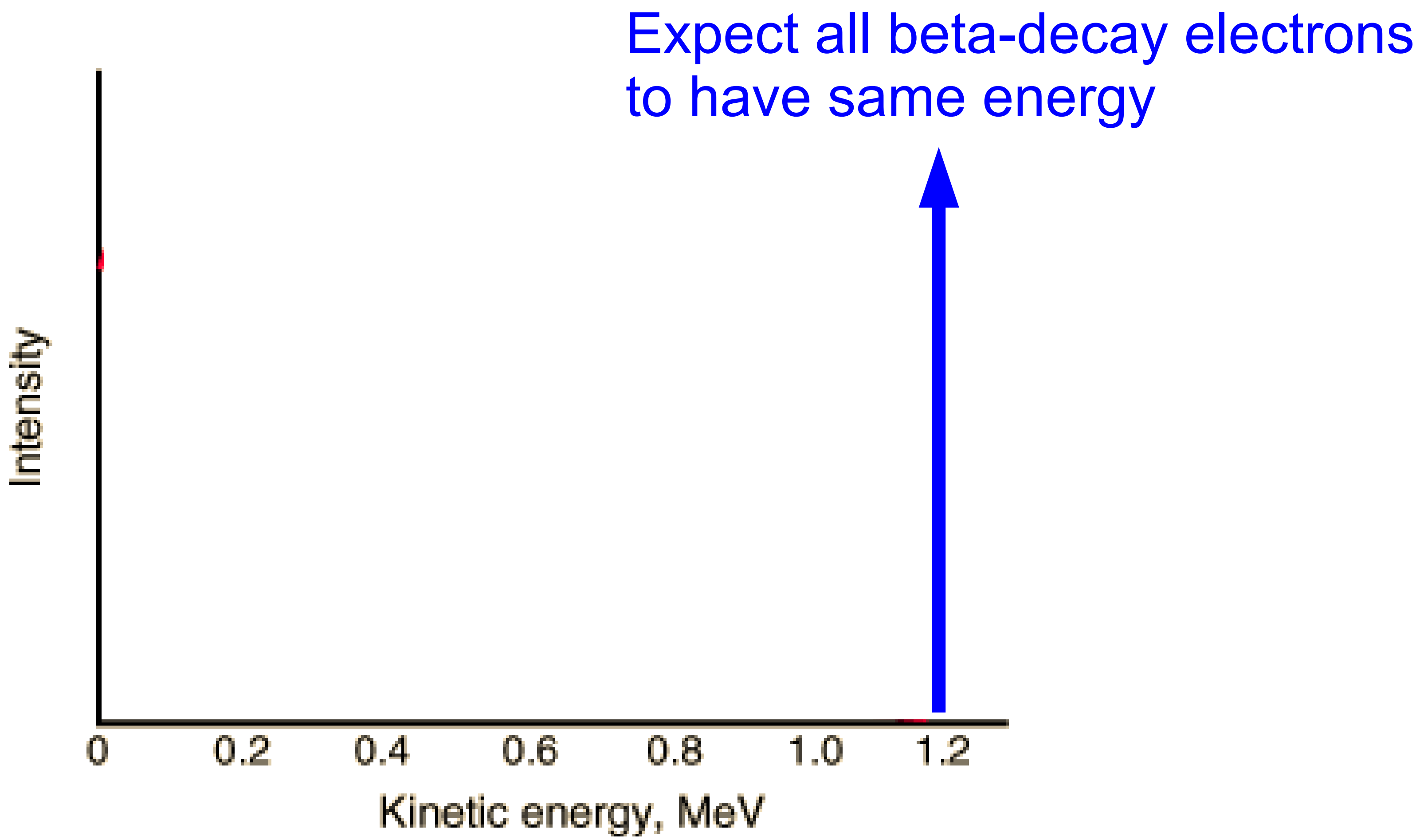
Electrons orbit nucleus of protons and neutrons .

Beta Decay



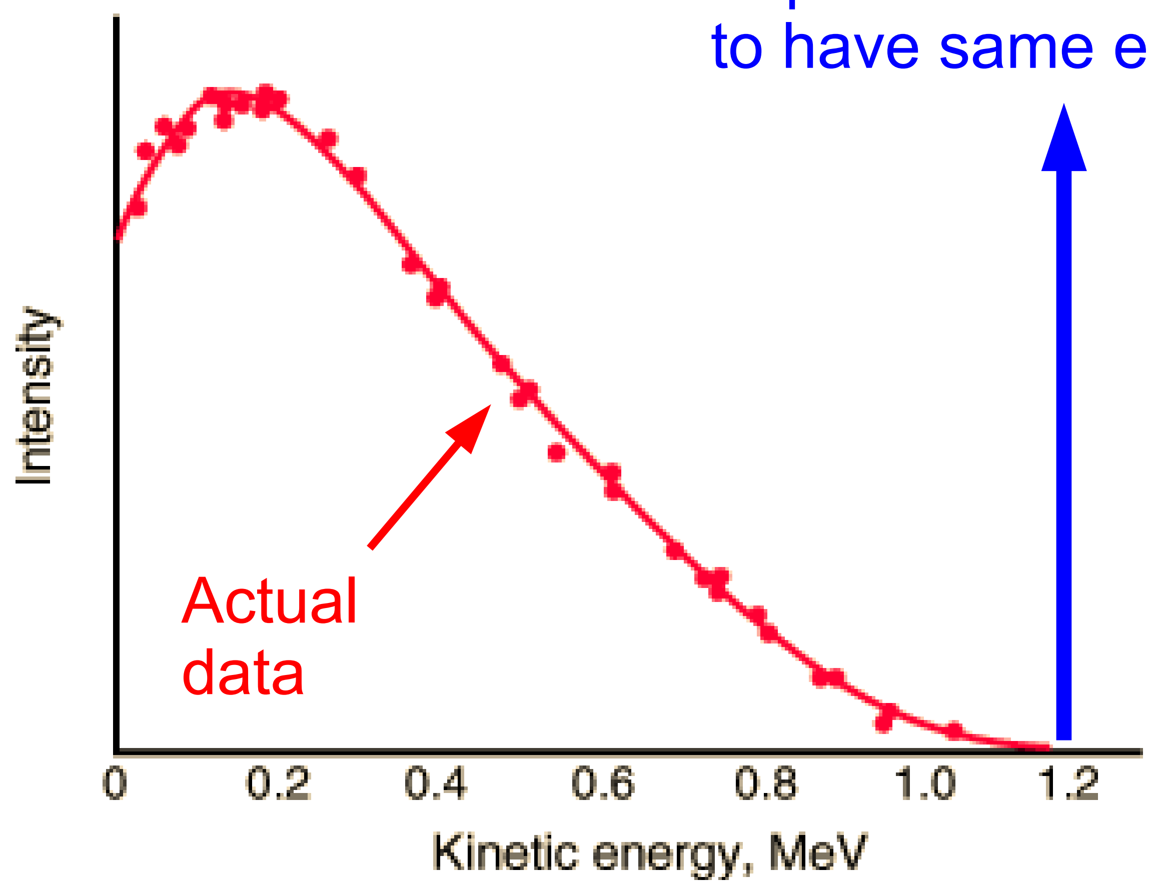
Neutron in the nucleus changes into a proton and emits an electron .

An Energy Crisis



An Energy Crisis

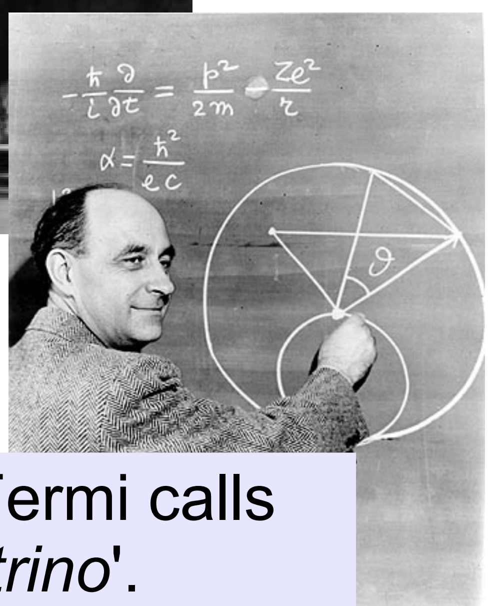
Expect all beta-decay electrons to have same energy



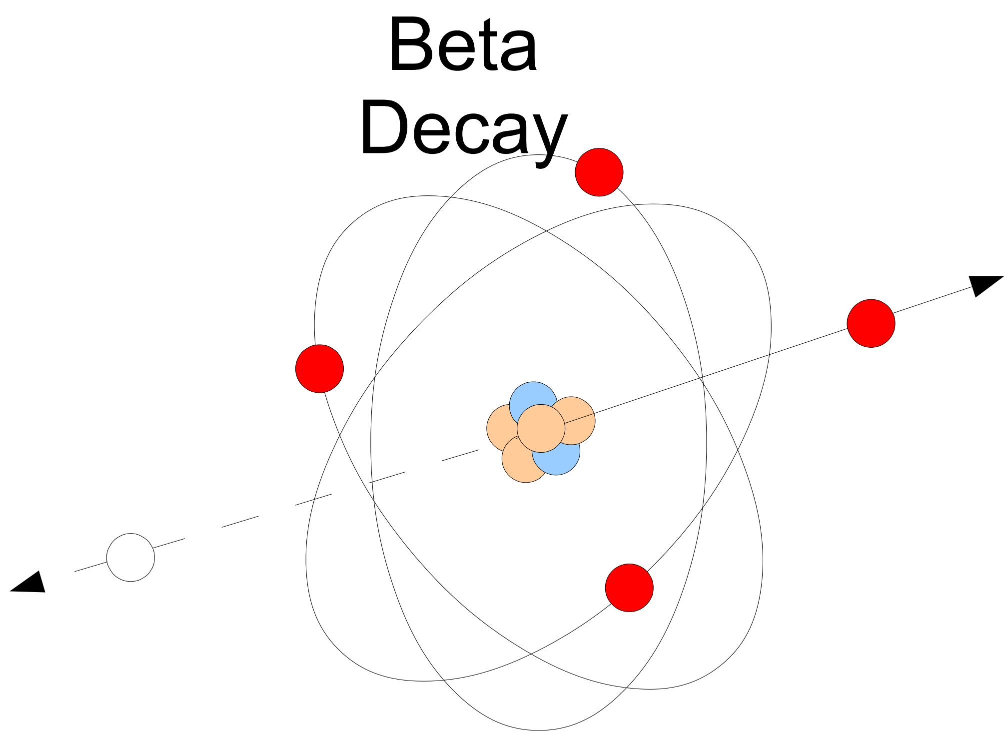
Where is missing energy going?

Are we missing something?

1930: W. Pauli suggests we are missing a particle.



1933: E. Fermi calls it the '*neutrino*'.



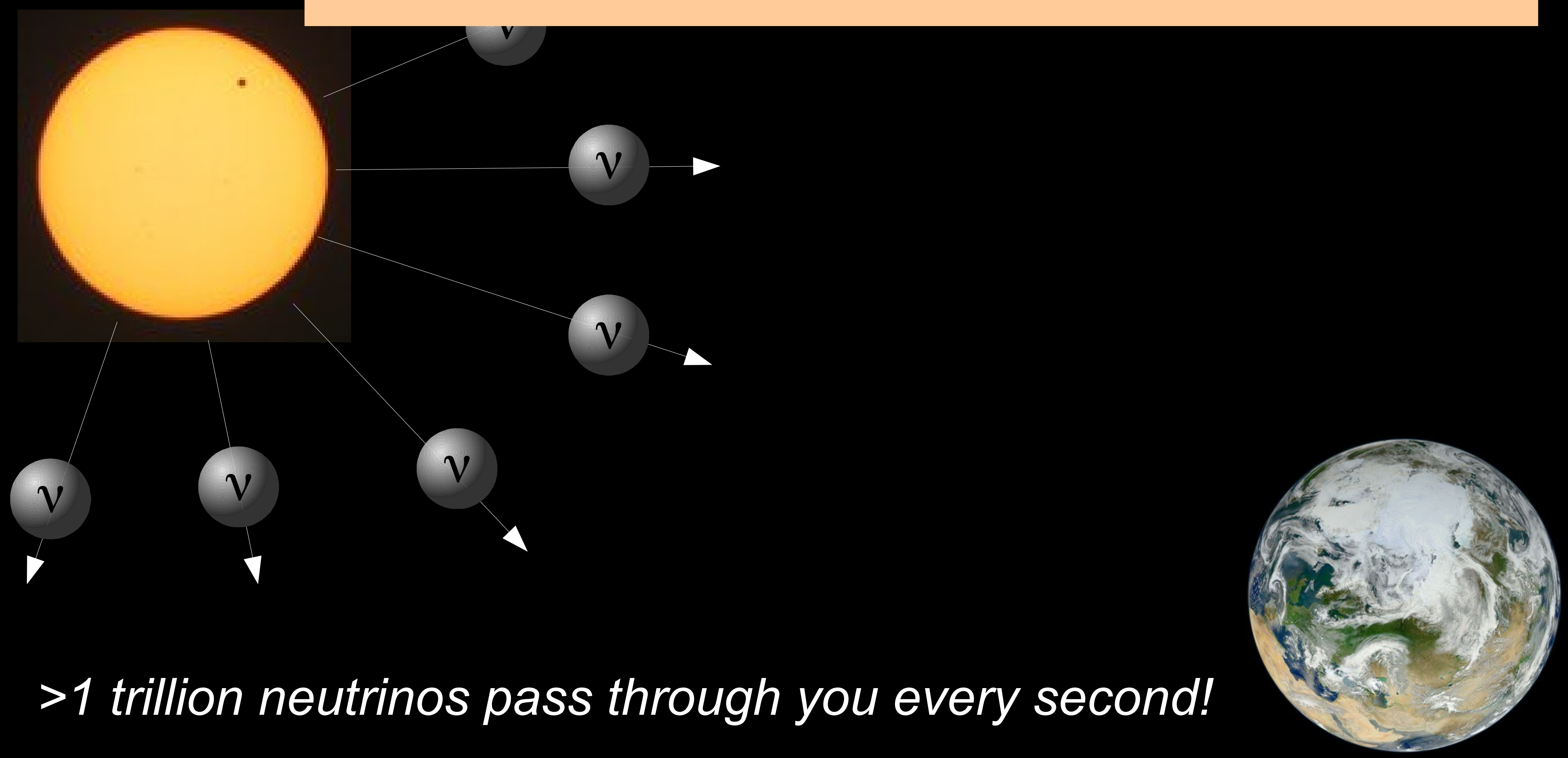
Neutron in the nucleus changes into a proton and emits an electron and an 'invisible' particle .

There goes the neighborhood

Introducing a new particle has consequences...

The Sun is intense!

The Sun shines in neutrinos as well as light.

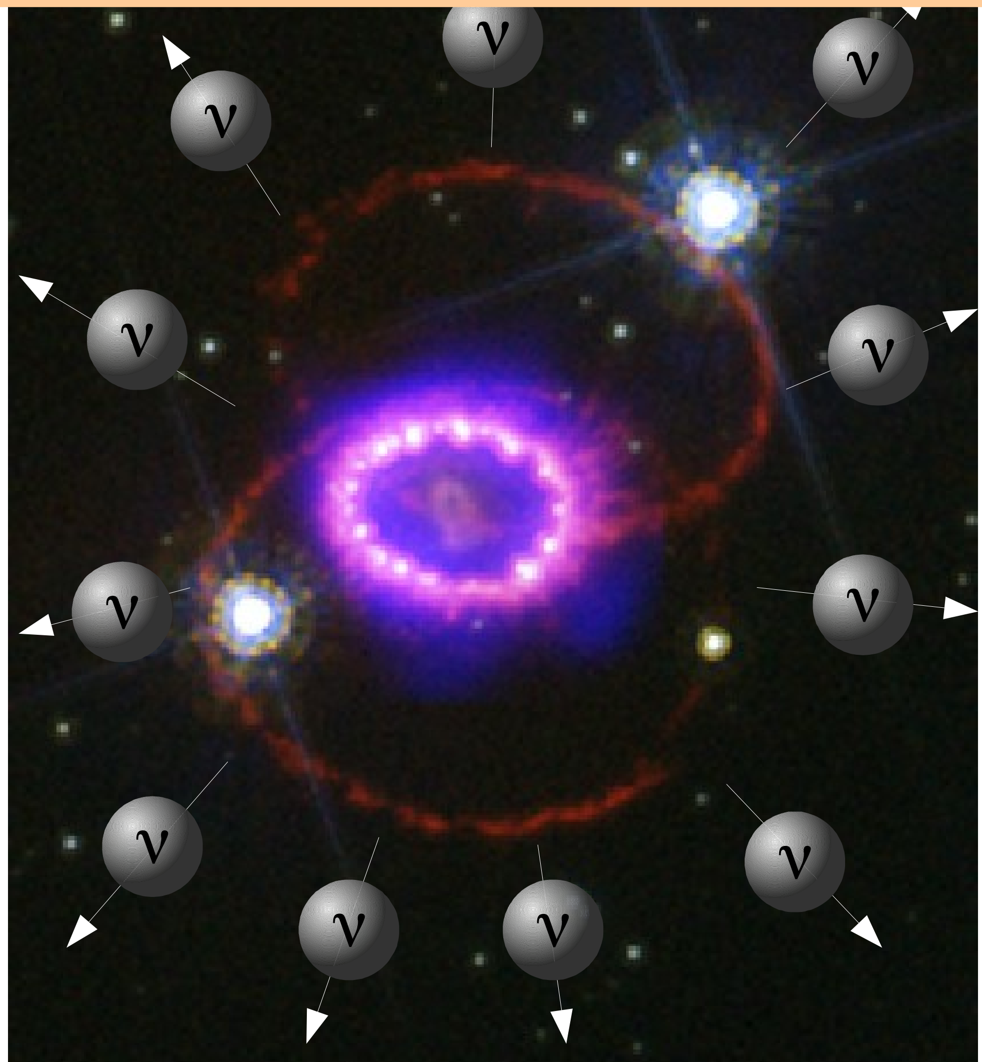


>1 trillion neutrinos pass through you every second!

earthobservatory.nasa.gov

What a blast!

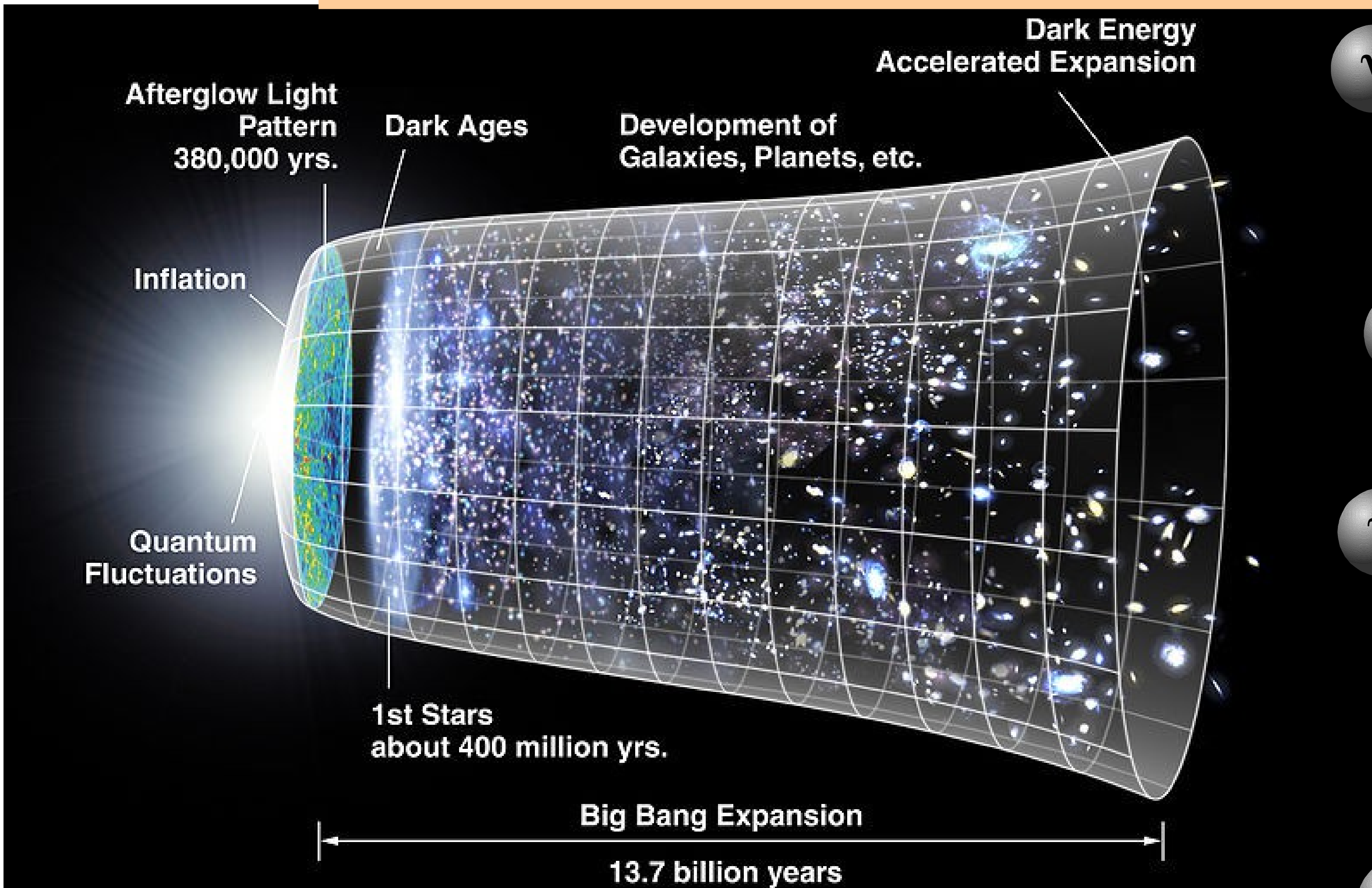
>99% of supernova energy is released in neutrinos!



Credit: X-ray: NASA/CXC/PSU/ S.Park & D.Burrows.; Optical: NASA/STScI/CfA/ P.Challis

Remains of the Party

Neutrinos still around from the Big Bang.

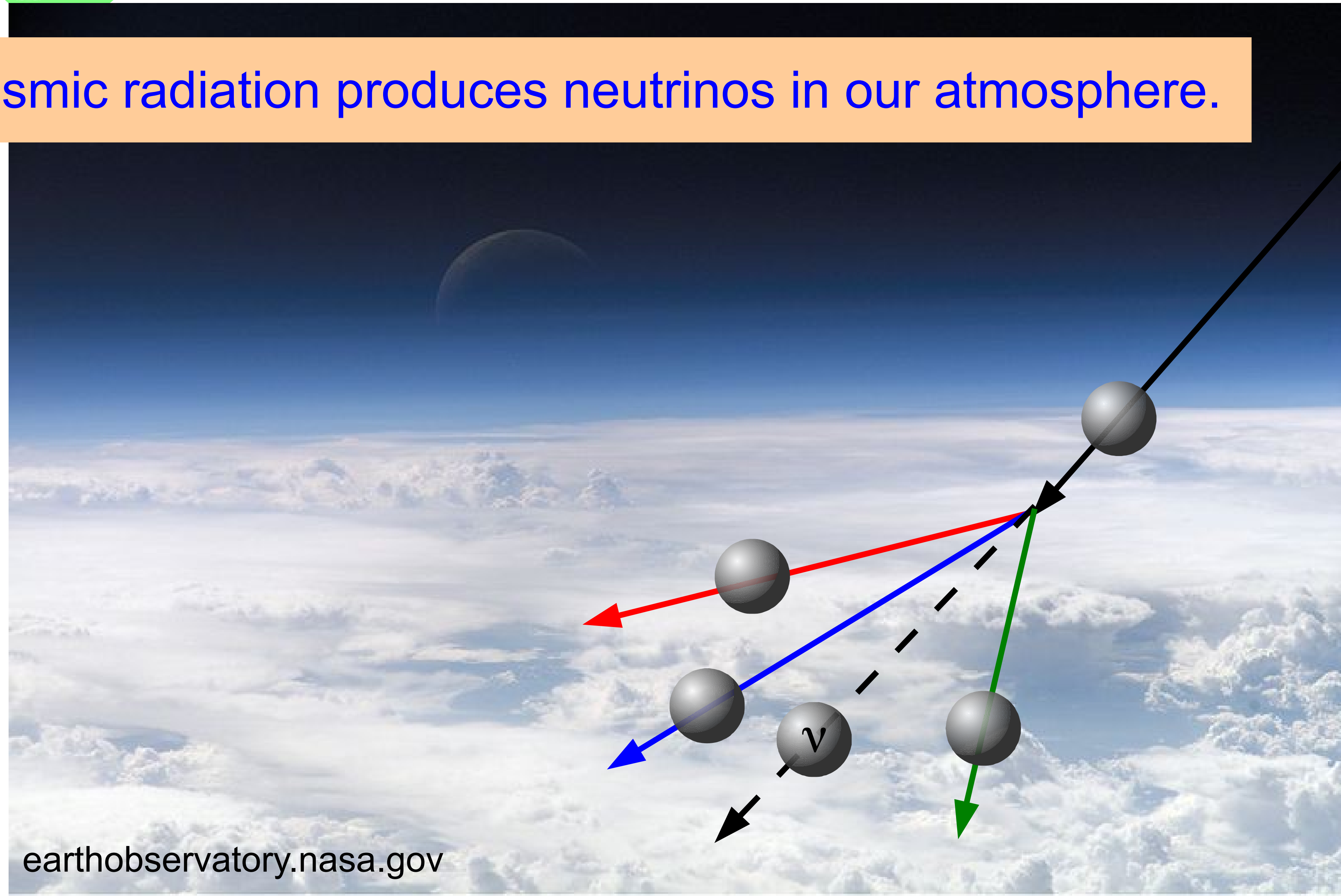


Credit: NASA/WMAP Science Team

Estimates of ~300 per cubic centimeter.

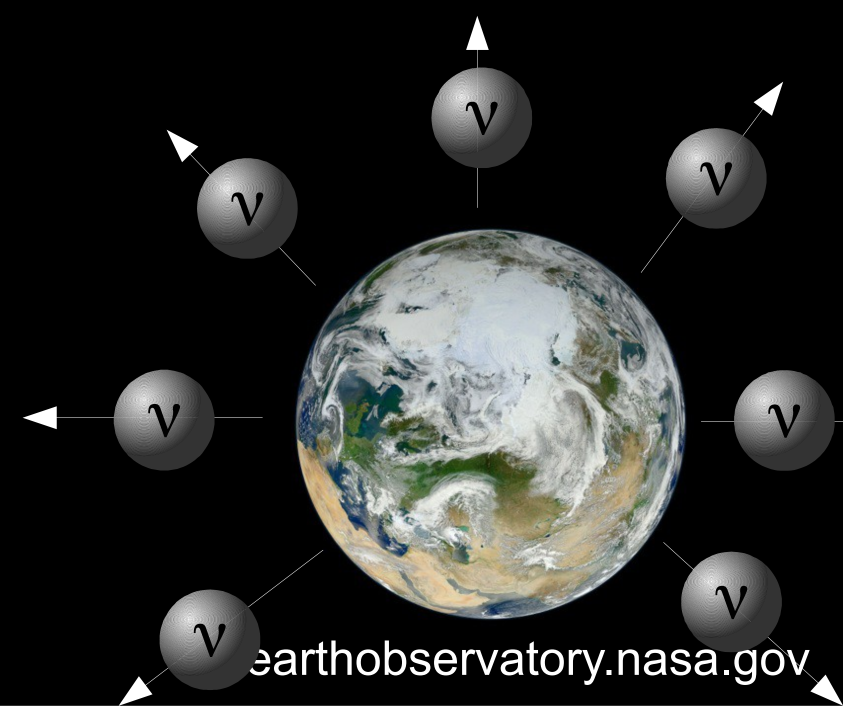
Neutrino Rain

Cosmic radiation produces neutrinos in our atmosphere.



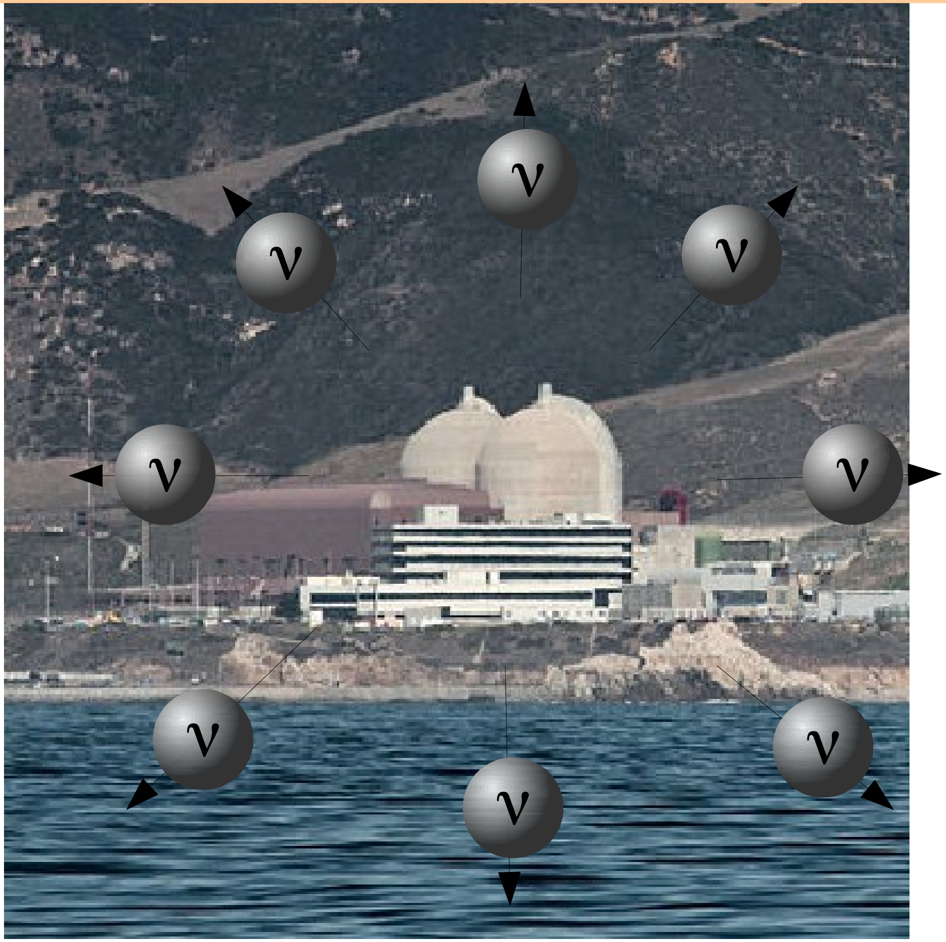
Earthshine

Natural radioactivity of the earth produces neutrinos



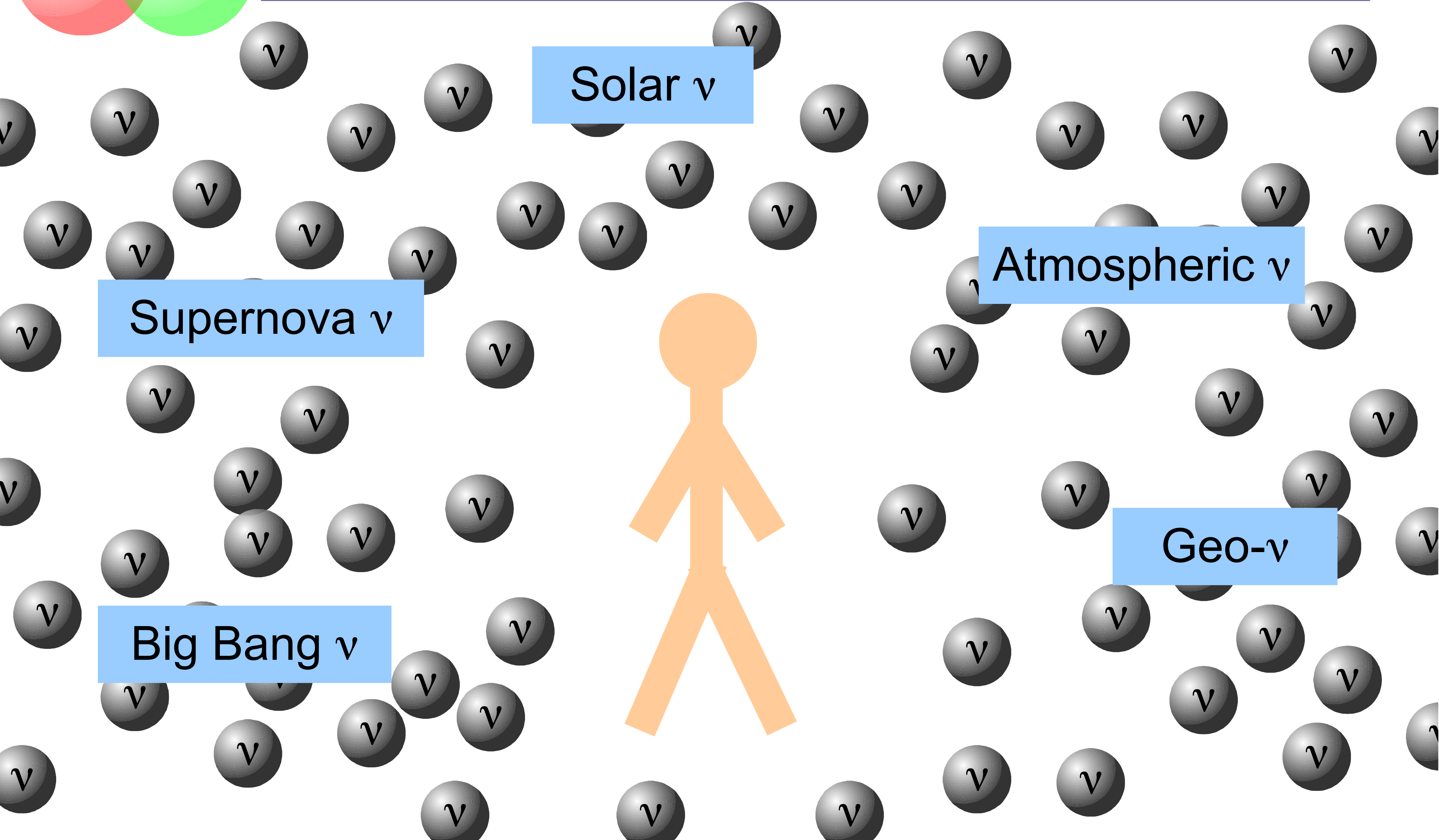
'Man-made' Neutrinos

A standard nuclear power reactor produces ~10^{21} neutrinos per second!

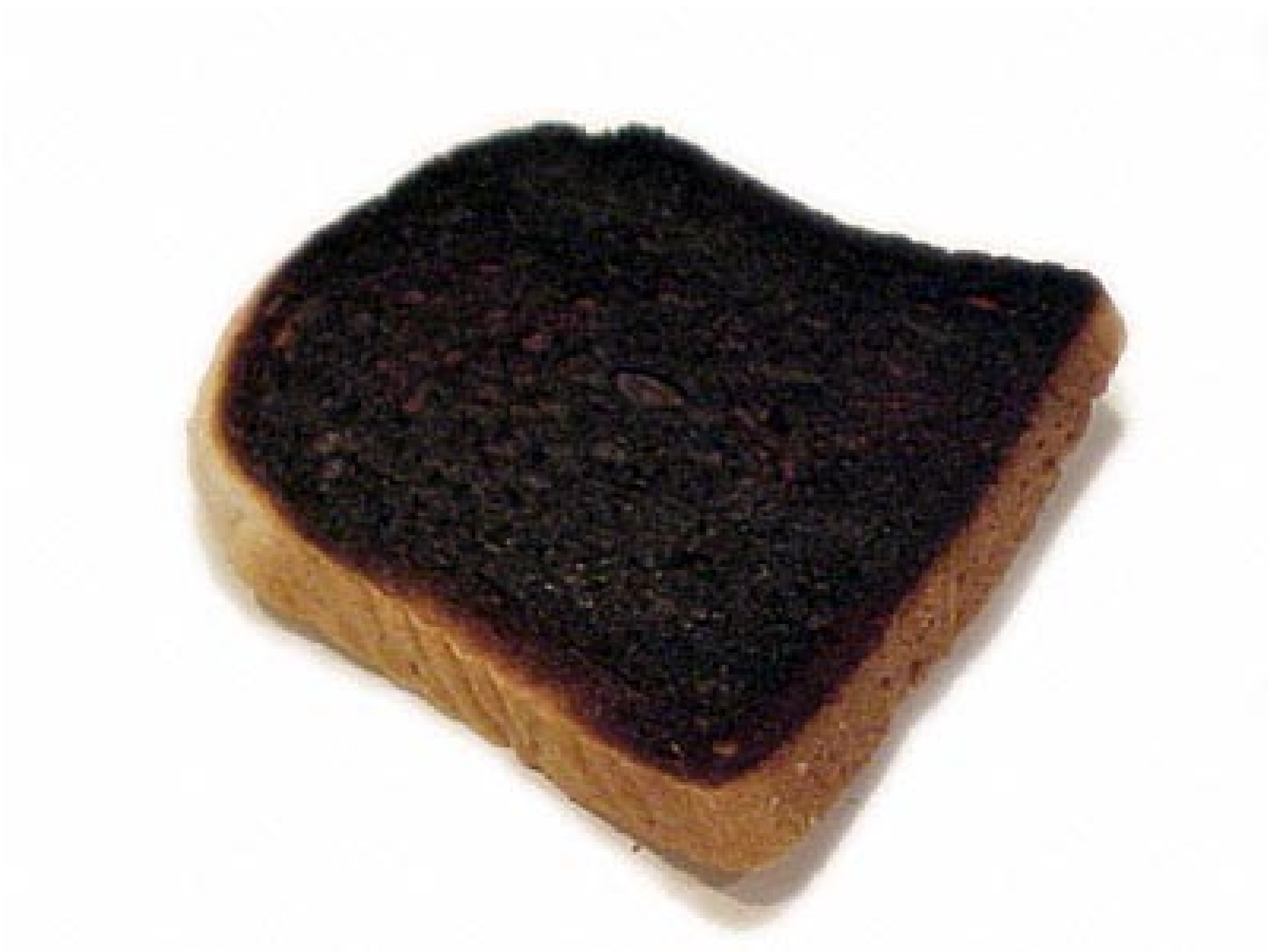


Credit: Mike Baird

Outnumbered!



Is something cooking?

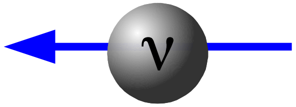


Glass Houses

We are 'transparent' to neutrinos.

To Stop a Neutrino...

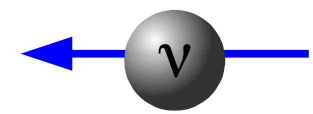
Let's build a wall...



To Stop a Neutrino...

Let's build a wall...

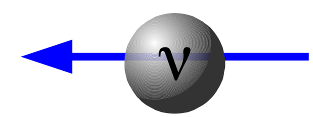
...a little thicker...



To Stop a Neutrino...

Let's build a wall...

...a little thicker...



...than our galaxy.

What about experiments?

No detection of neutrinos for ~20 years...

Act 2:
Neutrino experiments, great and not so great

In the real world...

Neutrino experiments are not easy...

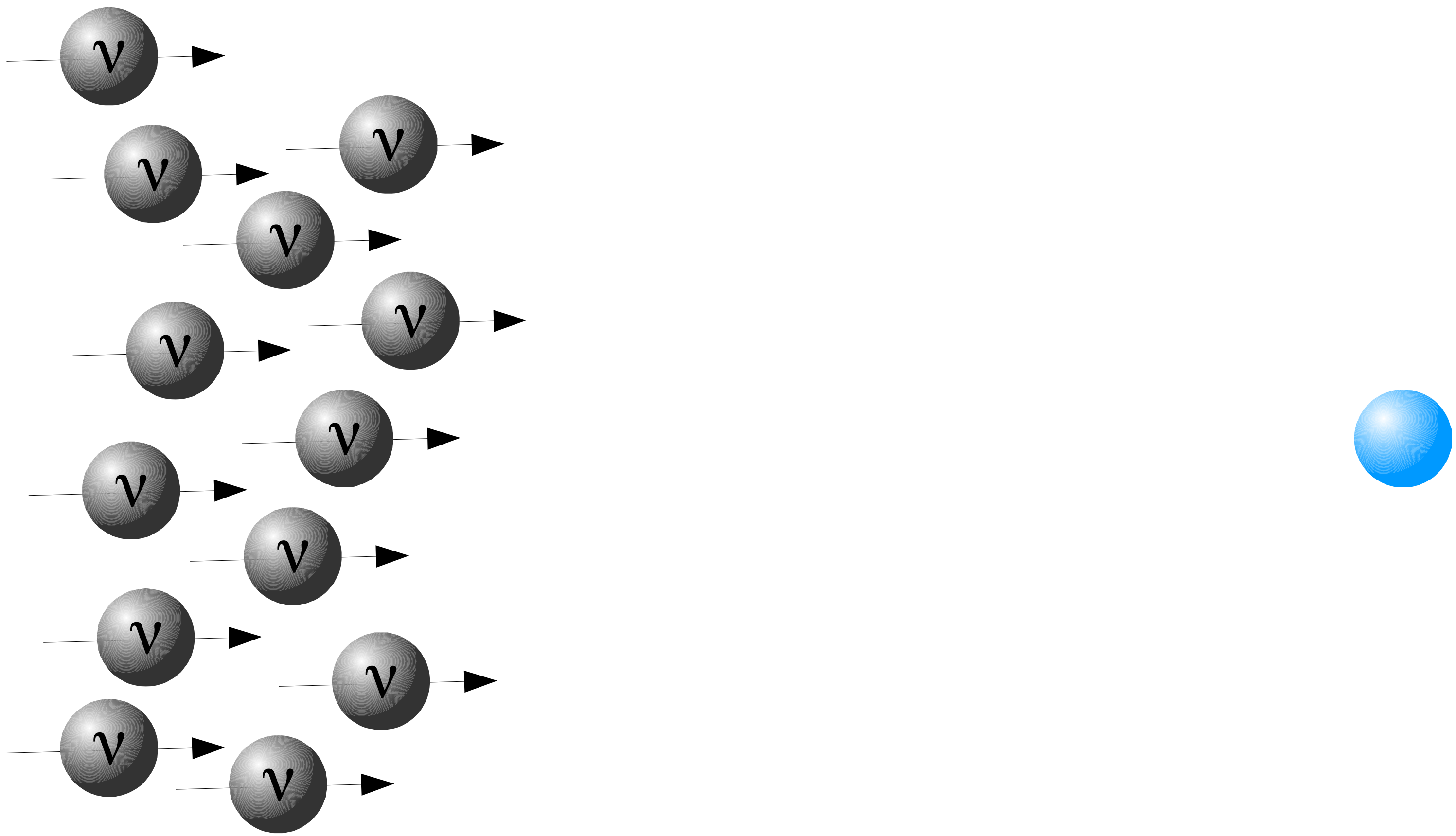
Just because you see the expected,
→ doesn't mean you're right.

Just because you see the unexpected,
→ doesn't mean you're wrong.

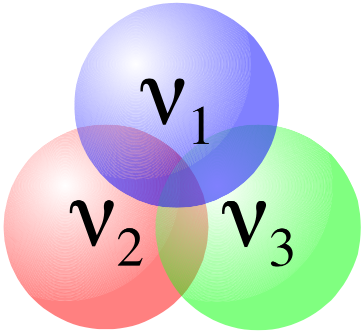
Playing the odds

The chance of a single neutrino interacting with a single particle
→ very small!

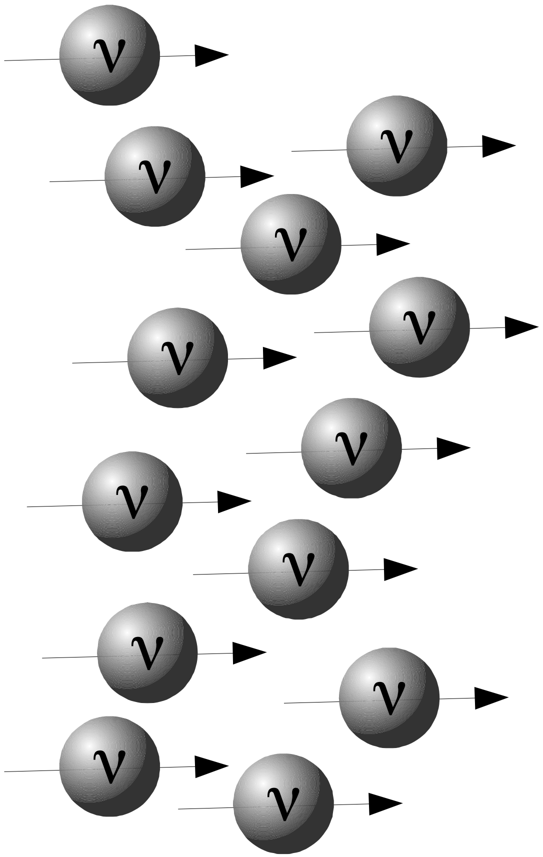
Playing the odds

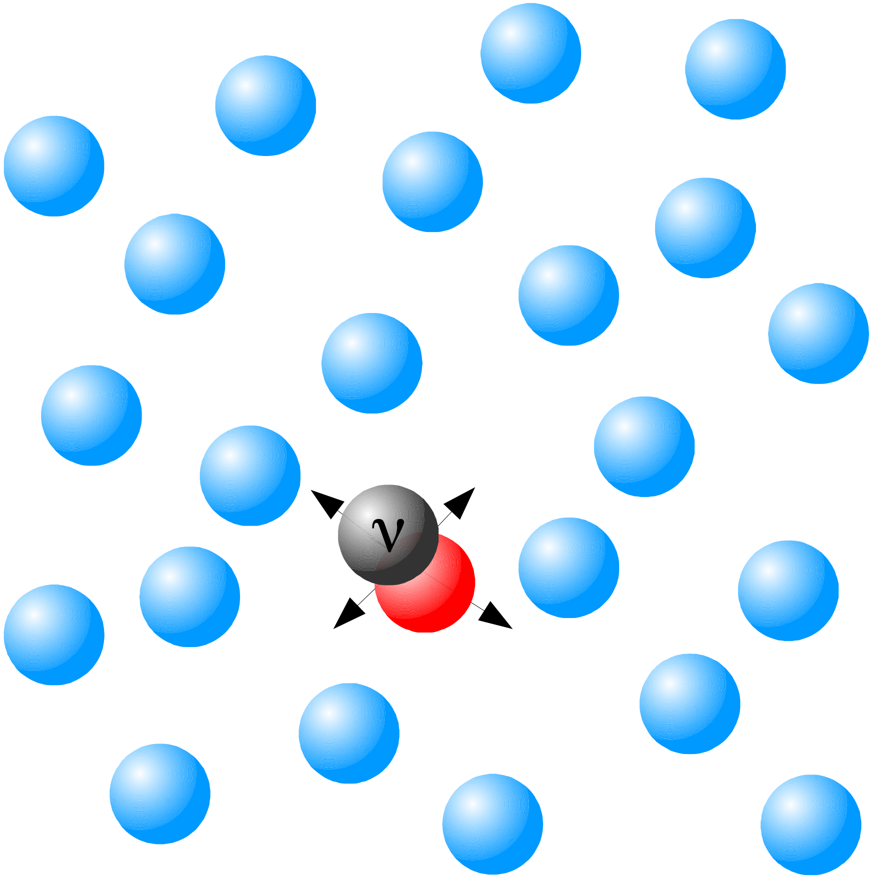


The chance of one of many neutrinos interacting with a single particle → still very small!



Playing the odds

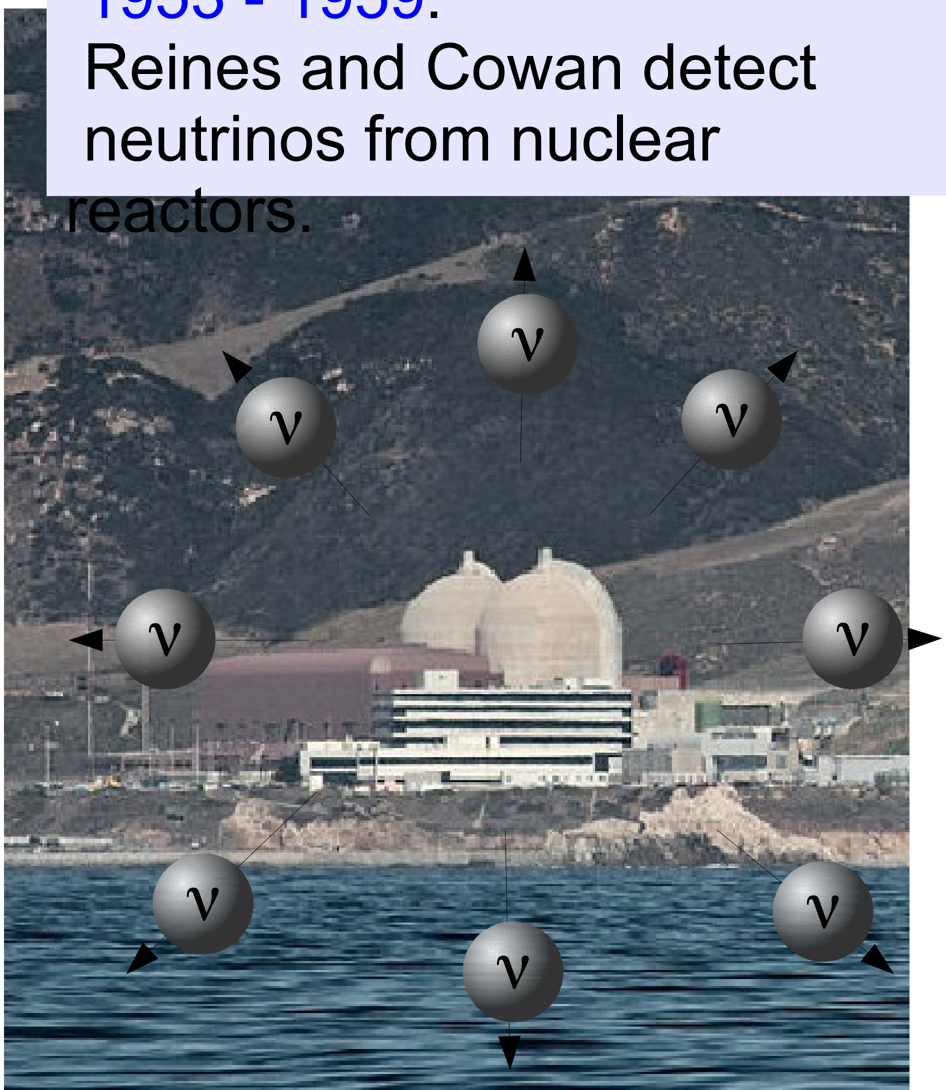


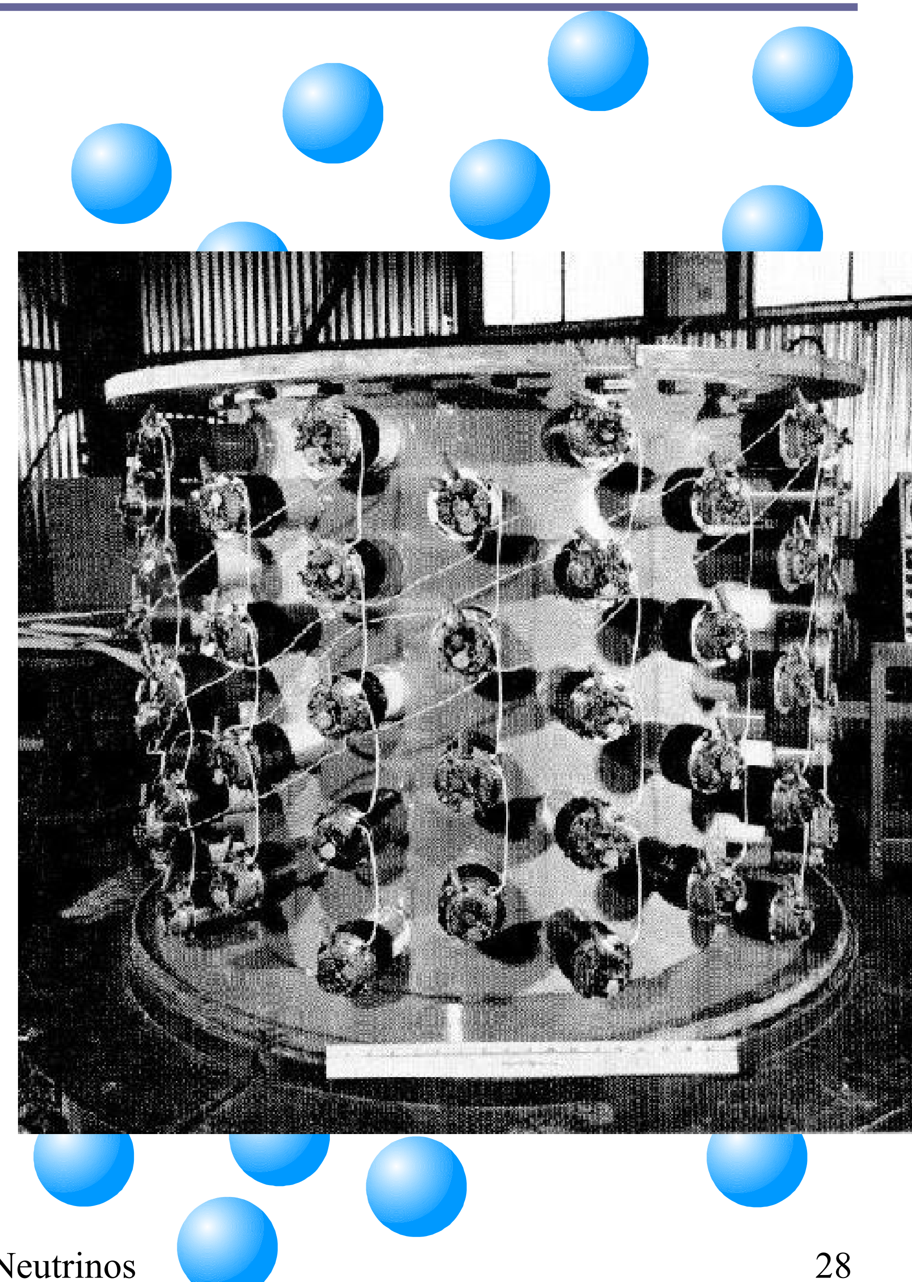


The chance of one of many neutrinos interacting with one of many particles
→ still very small, but it might just work...

Numbers Big and Small

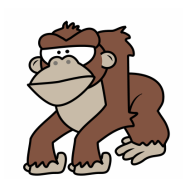
1953 - 1959:
Reines and Cowan detect neutrinos from nuclear reactors.



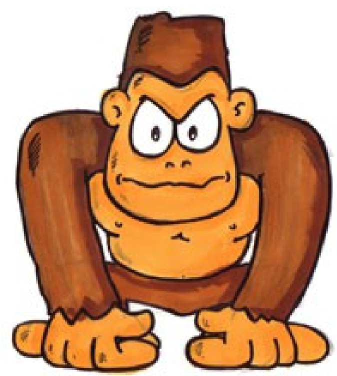


Electron's Big Brothers

Electron: e

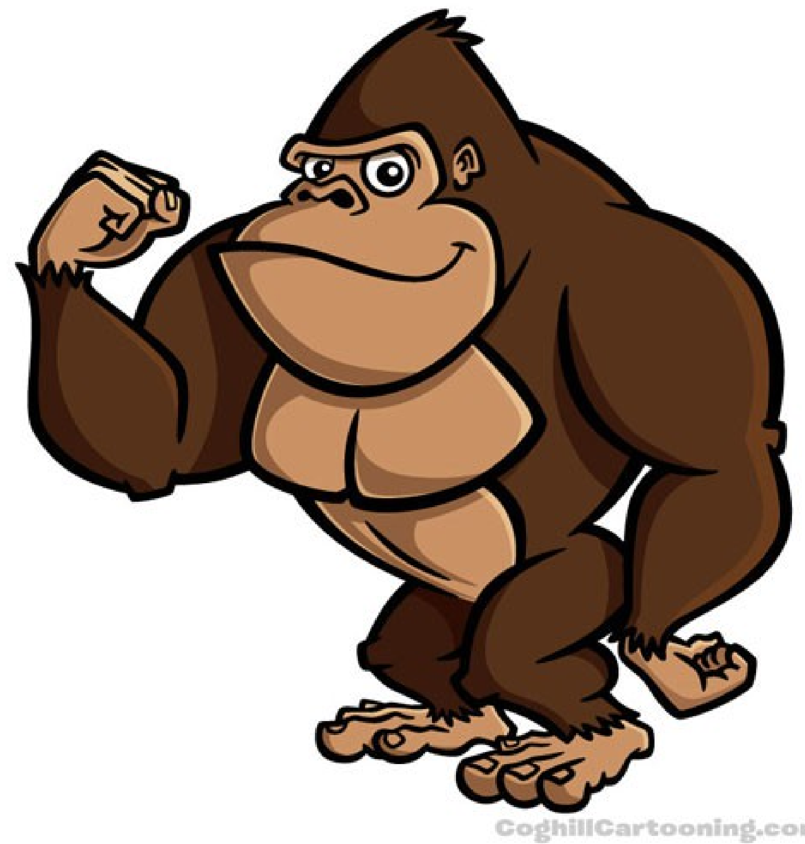


Muon: μ



~200 times heavier

Tau: τ



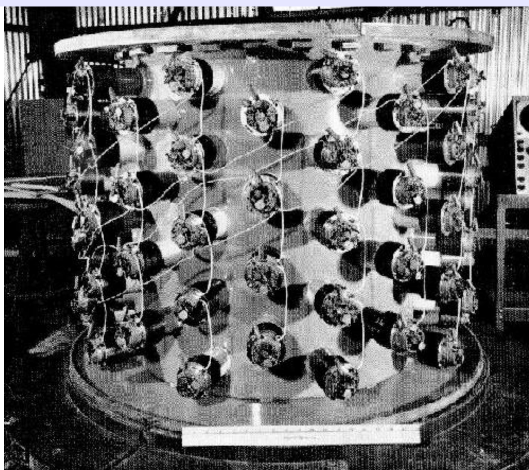
~3500 times heavier!

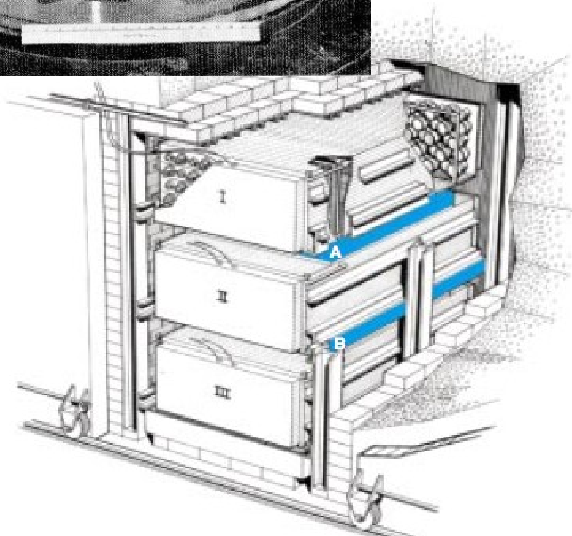
Physicists call this *'Flavor'*.

Pick your Flavor

ν_e

1953 - 1959:
Reines and Cowan detect neutrinos from nuclear reactors.



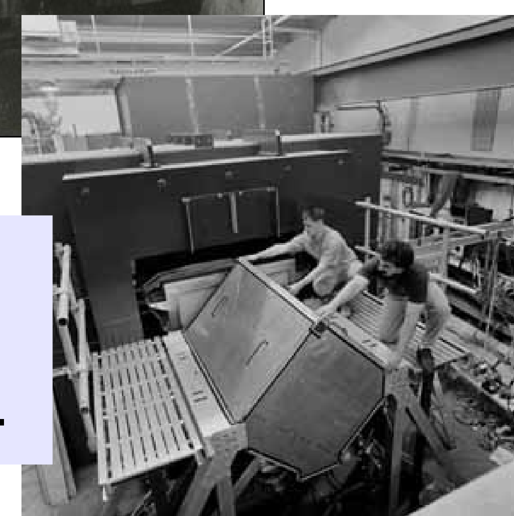


ν_μ

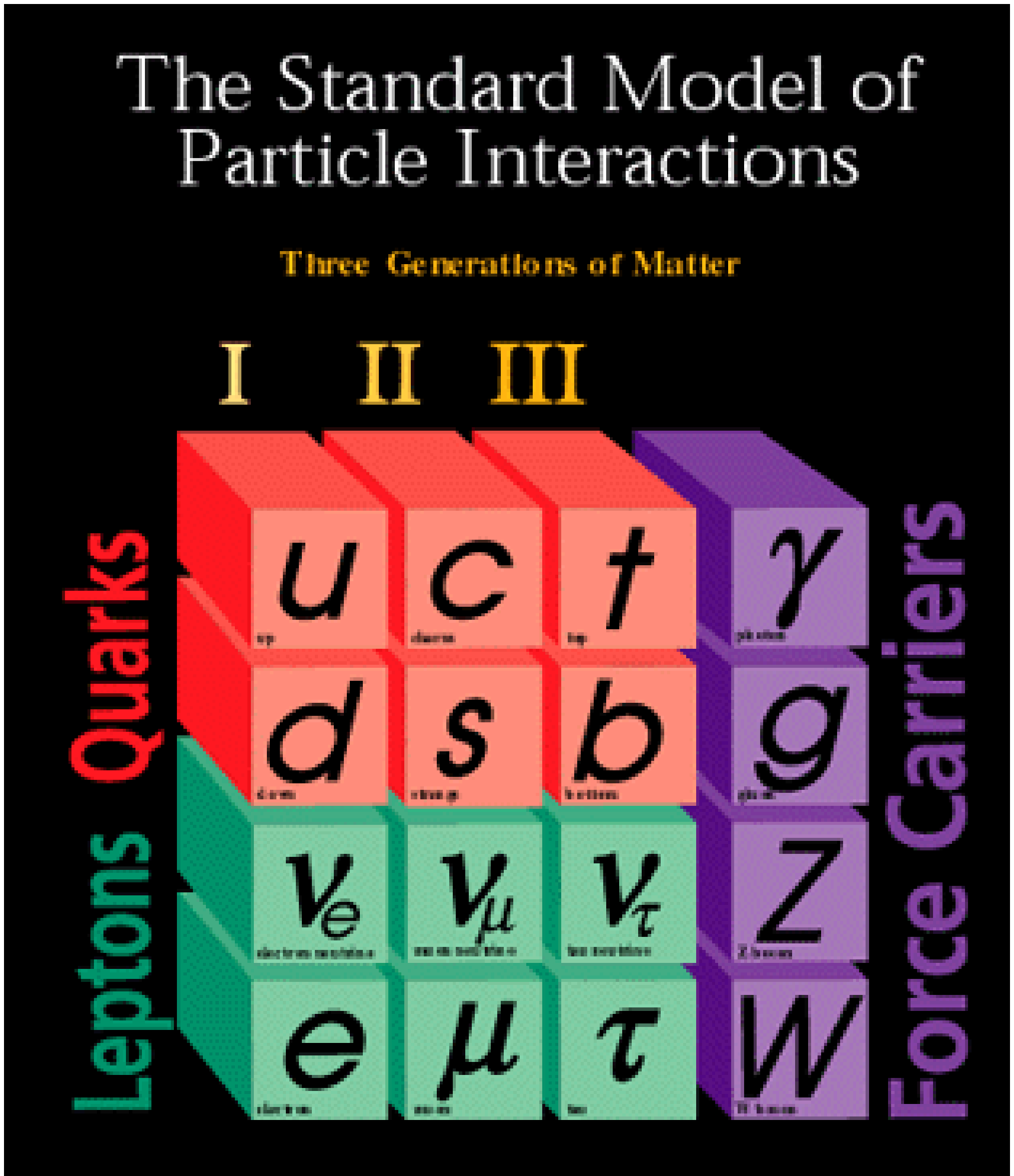
1962:
Lederman, Schwartz, Steinberger detect muon neutrino.

ν_τ

2000:
DONUT experiment detects tau neutrino.



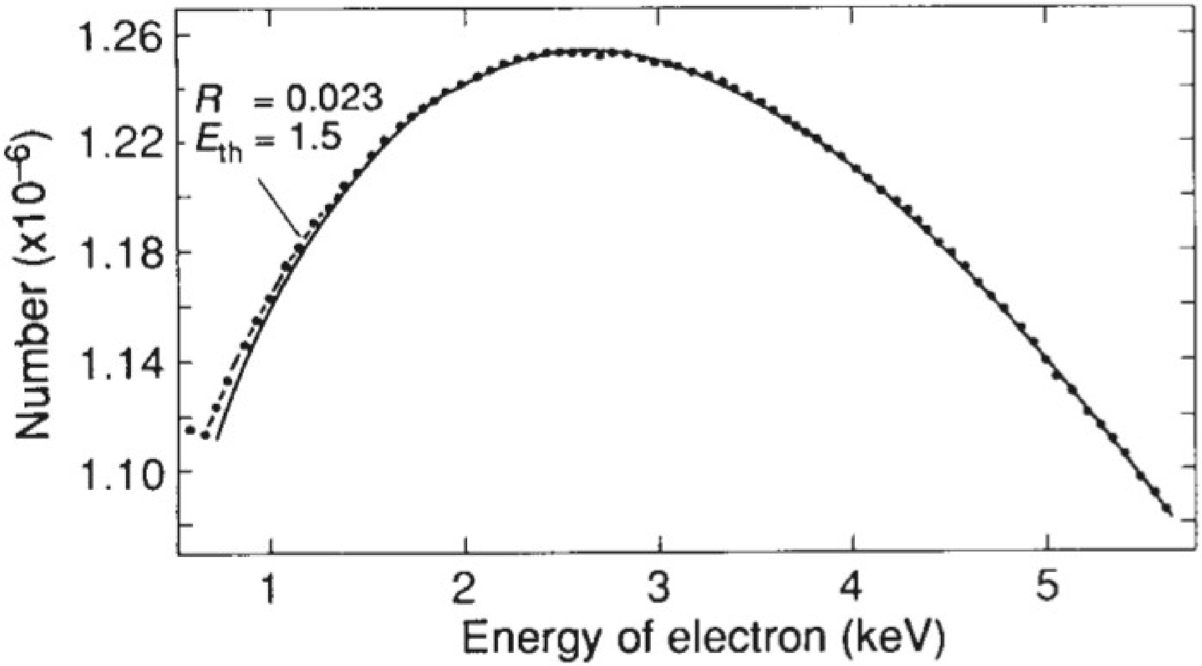
The Standard Model

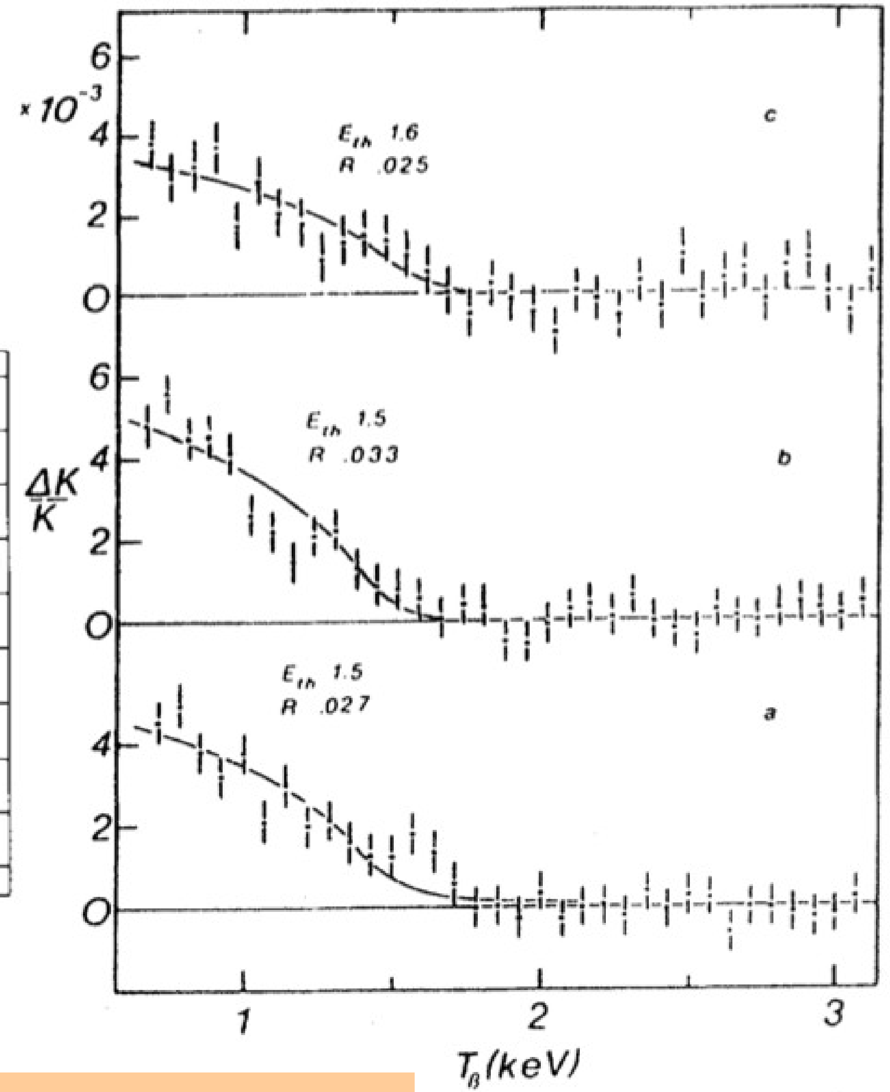


Neutrinos:
- Three flavors
- Massless

A kink appears...

1985:
J.J. Simpson reports distortion of beta decay spectrum.

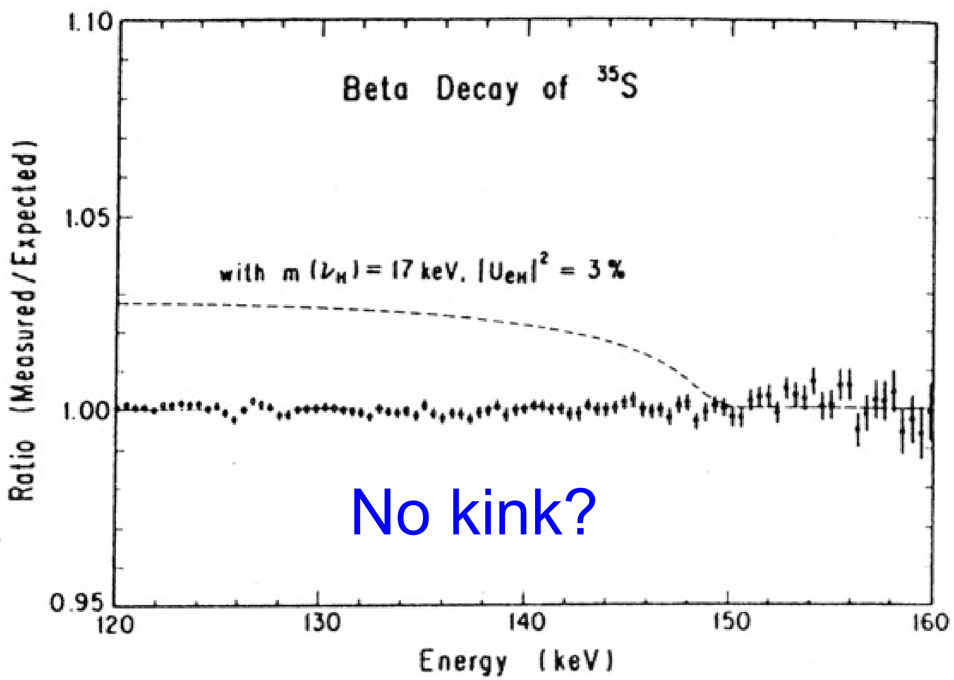




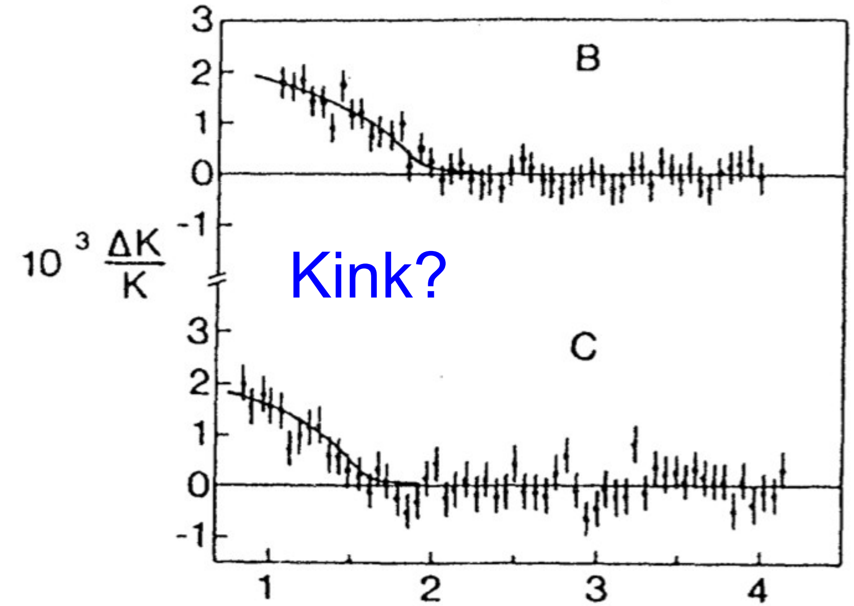
Considered evidence of neutrino mass (17 keV)

To kink or not to kink...

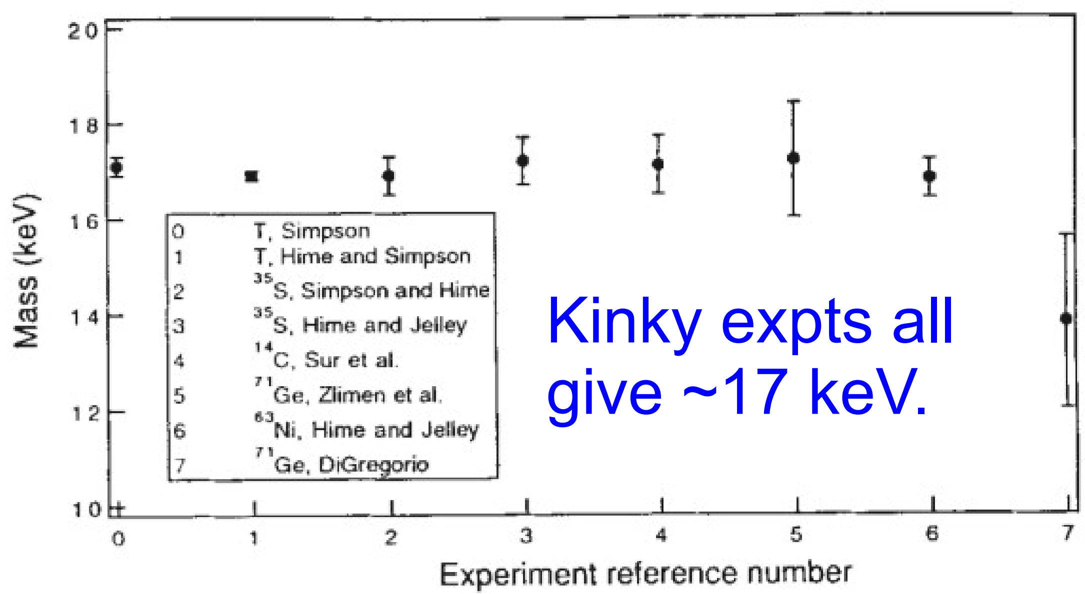
1985-1992:
Mixed results from experiments



No kink?



Kink?

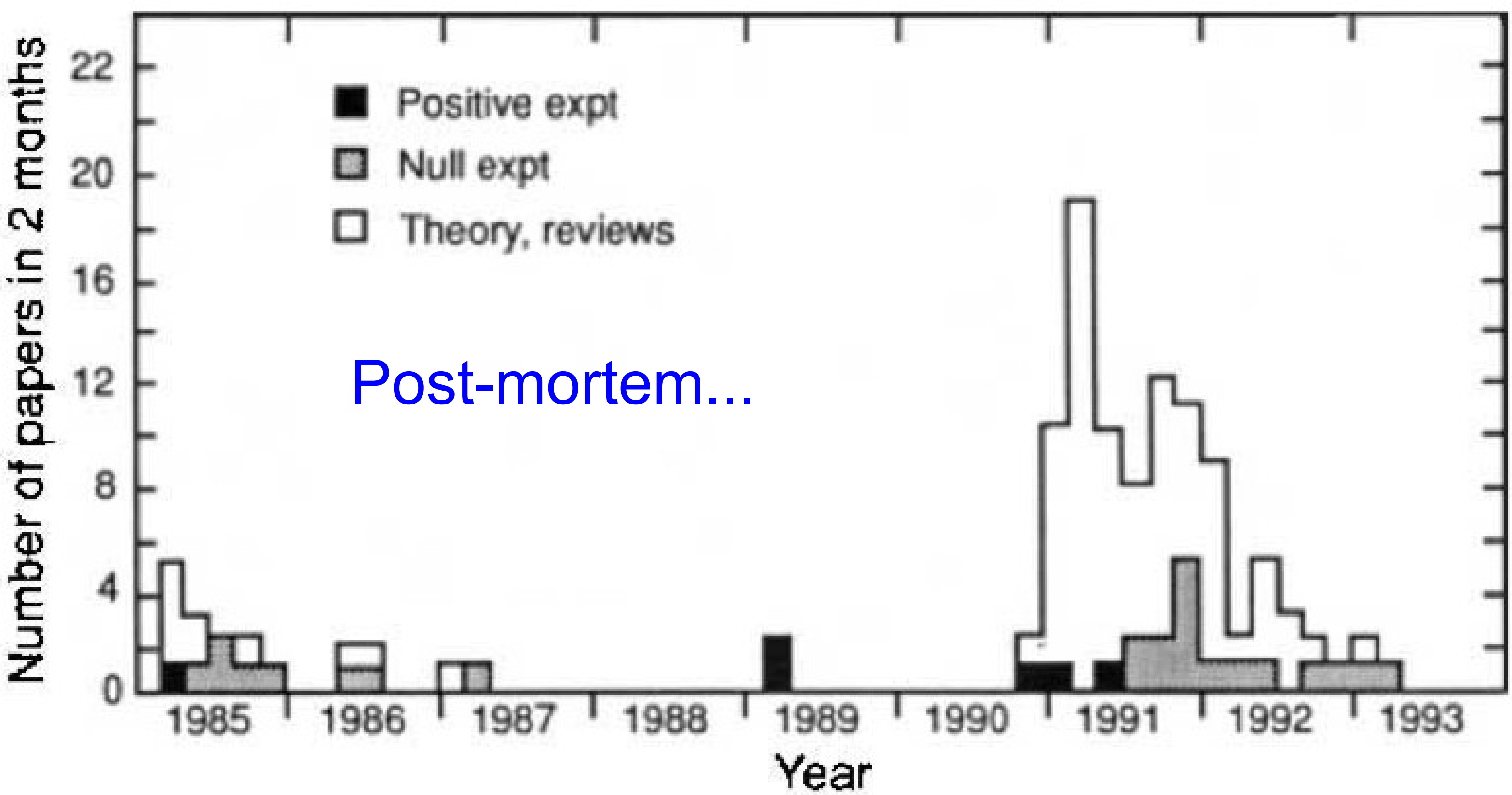


Kinky expts all give ~17 keV.

“The kink is dead!”

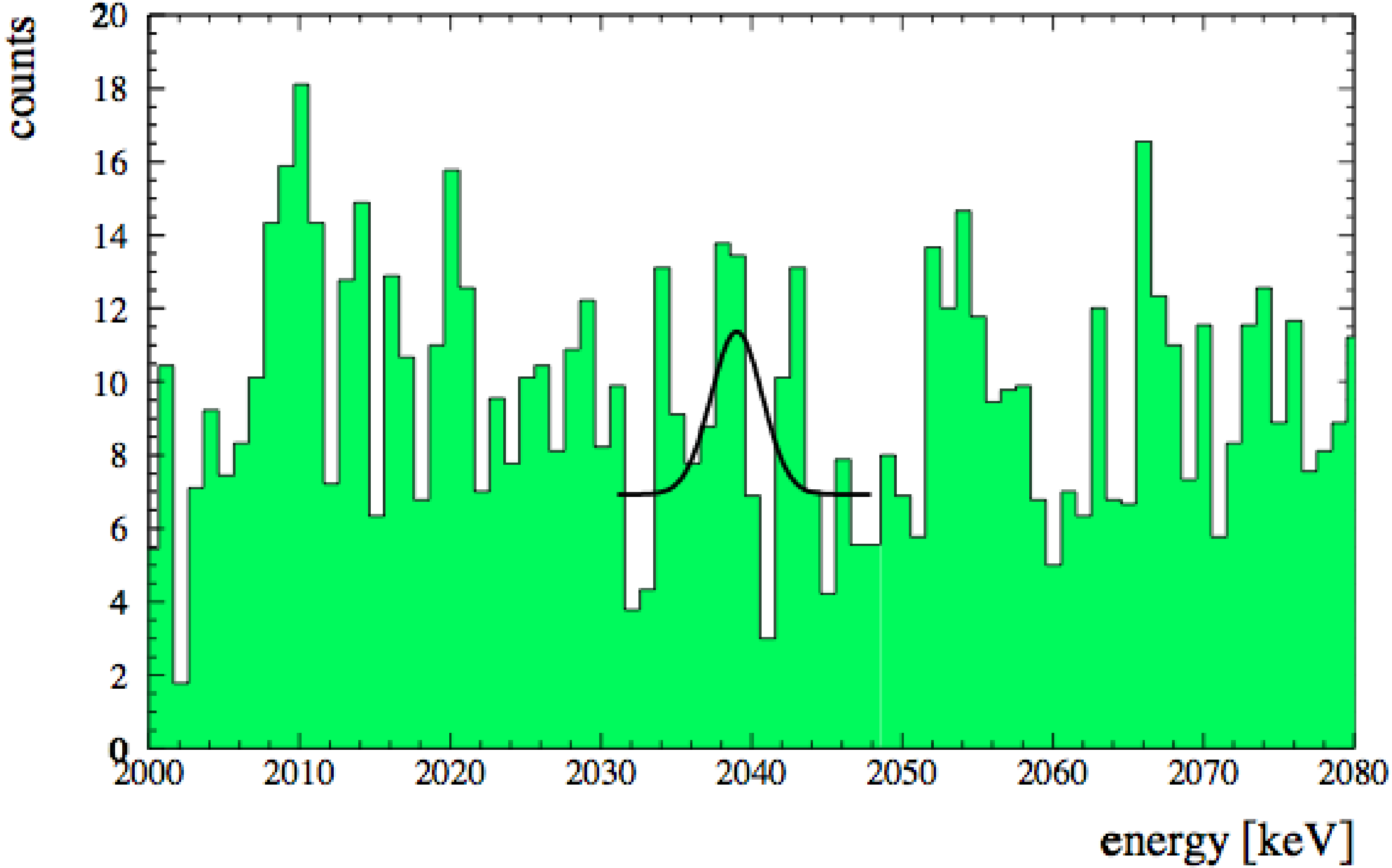
1993:

Detailed new experiments plus cross-checks of old experiments
→ Consensus that kink was experiment artifact.



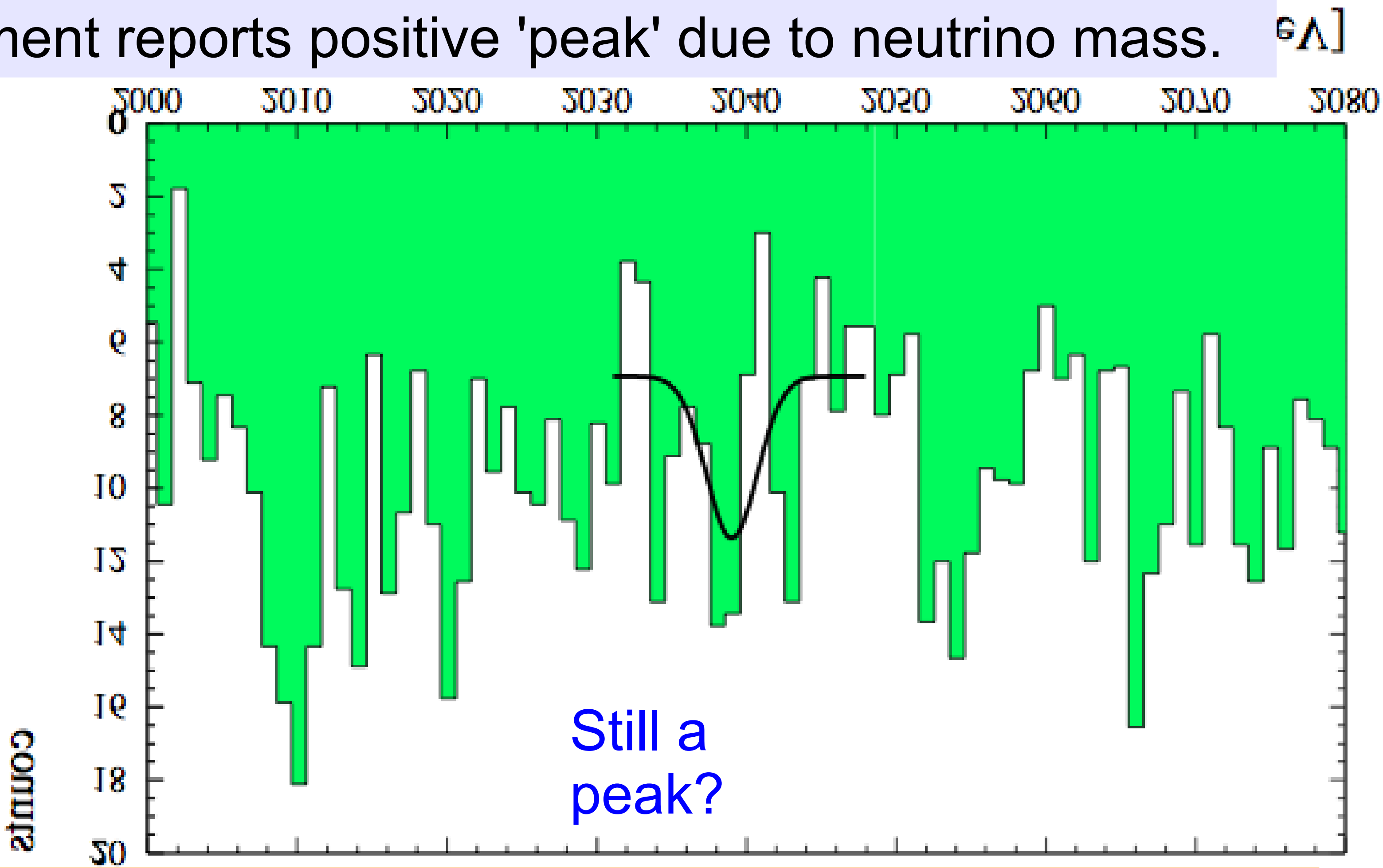
Neutrino Mass?

2001:
Experiment reports positive 'peak' due to neutrino mass.



Neutrino Mass?

2001:
Experiment reports positive 'peak' due to neutrino mass.



Jury is still out, but new experiments will soon check...

A Night at the Opera...

Sep. 2011: OPERA experiment reports neutrinos travel faster than light!

The New York Times

OUT THERE

The Trouble With Data That Outpaces a Theory

Elwood H. Smith

By DENNIS OVERBYE
Published: March 26, 2012

The British astrophysicist Arthur S. Eddington once wrote, “No experiment should be believed until it has been confirmed by theory.”

RECOMMEND

TWITTER

Mar. 2012:
Other experiments (ICARUS, Borexino, LVD) do not find faster-than-light ν.

OPERA finds errors in experiment.

Another problem?!

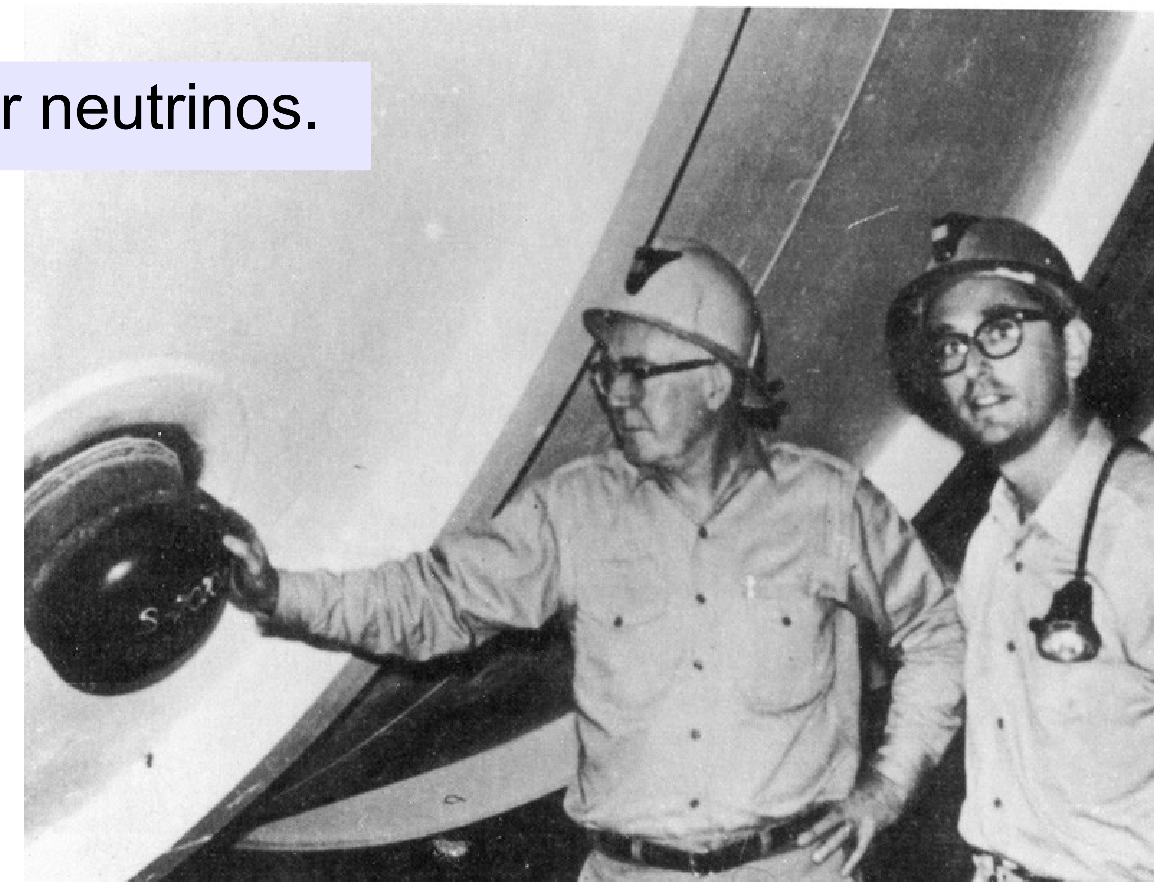
1968: R. Davis measures solar neutrinos.

Step 1:
Fill a tank with 100,000 gallons of cleaning fluid (Clorine).

Step 2:
Put it ~1 mile underground.

Step 3:
Wait for solar neutrinos to convert a few Cl atoms to Ar.

Step 4:
Take Argon atoms out of tank and count them.

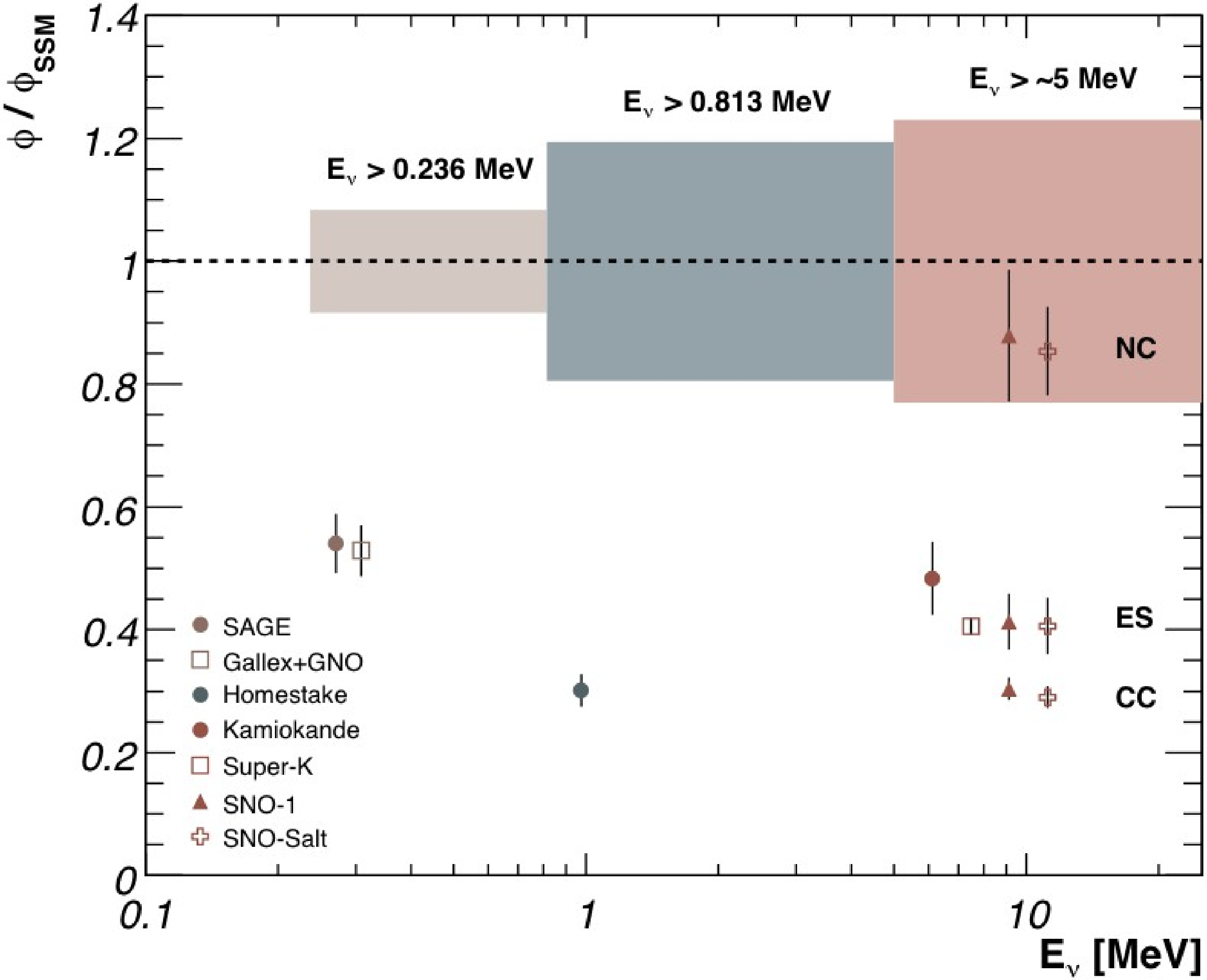


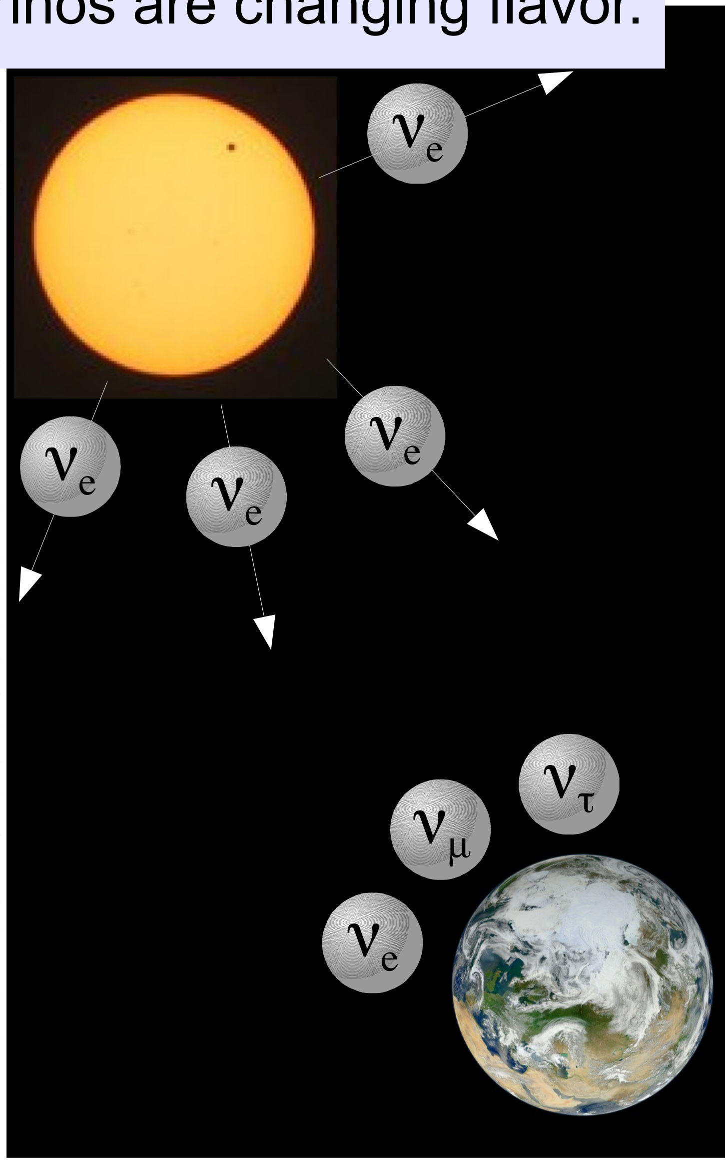
Only found 1/3 of expected neutrinos...

Act 3:
Neutrino Oscillation
and
The Daya Bay Experiment

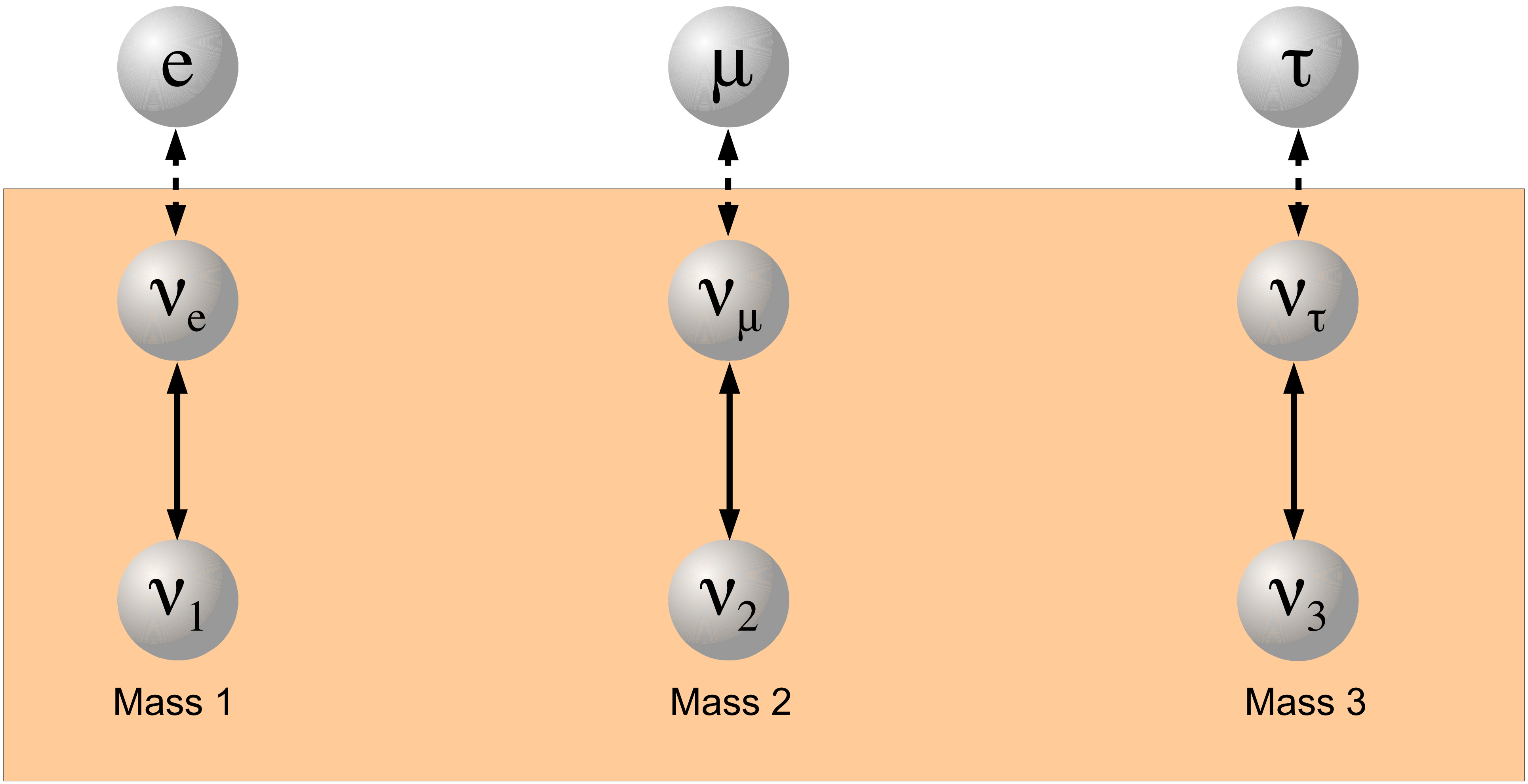
Back to the Sun...

2002: SNO experiment shows solar neutrinos are changing flavor.





Mixed-up Neutrinos



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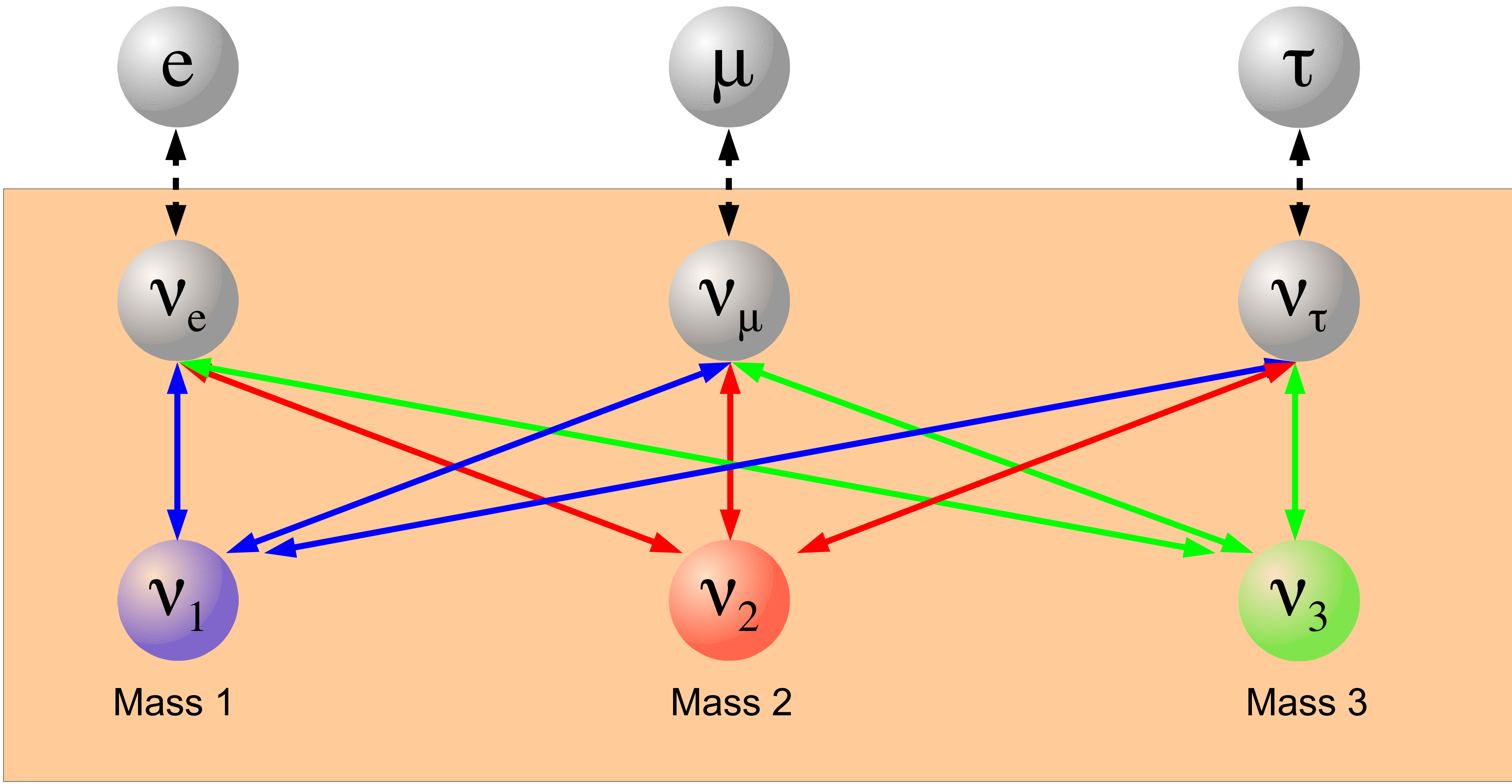
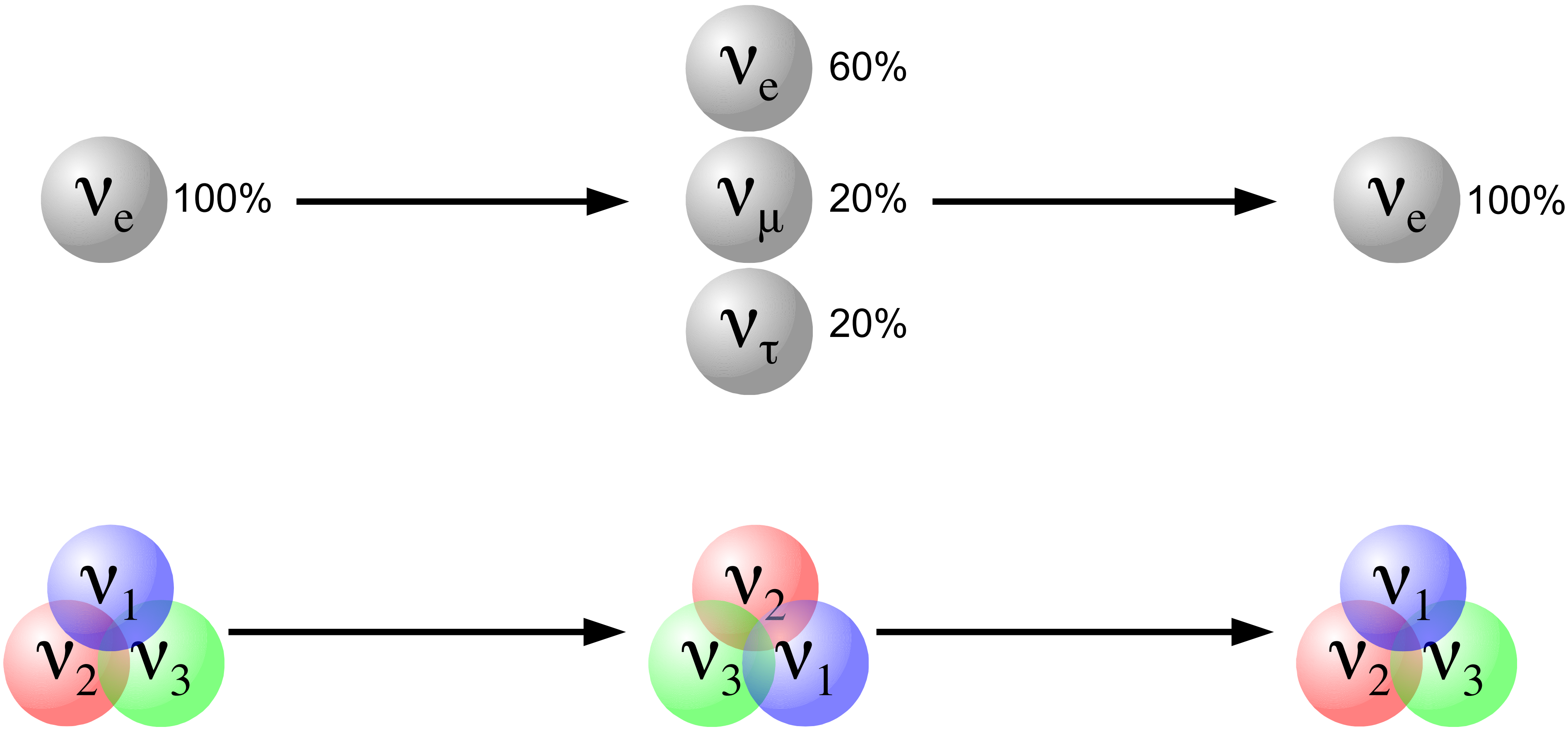
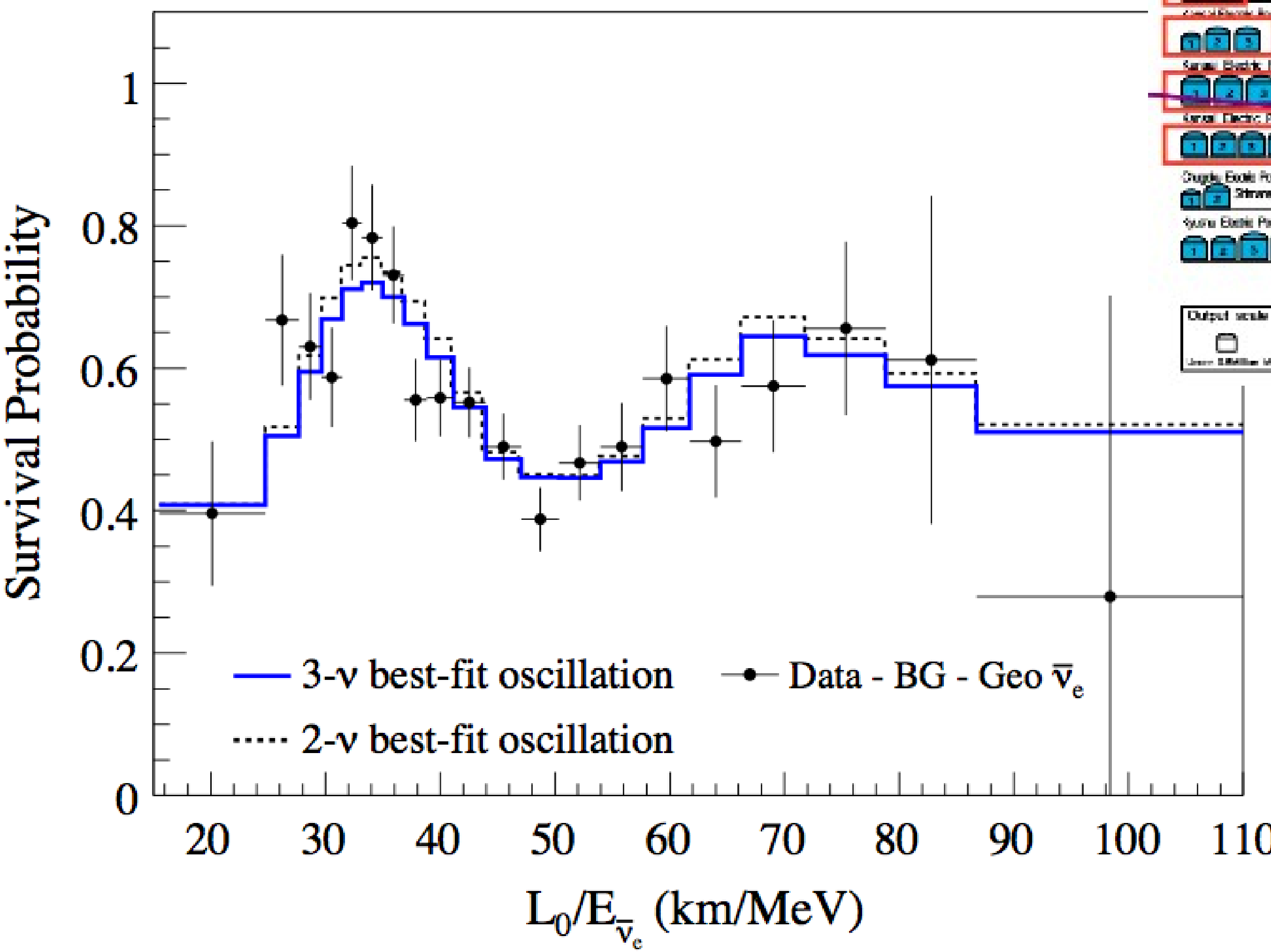


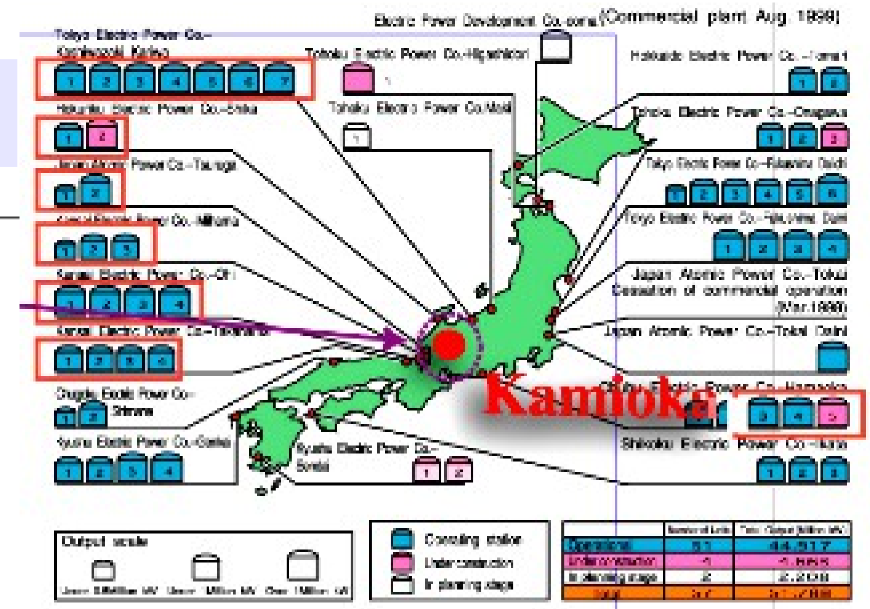
Neutrino Oscillation



Neutrinos do Oscillate!

2005: KamLAND shows signal of oscillation!





θ-what?

Amount of oscillation is described using three numbers:

$\theta_{12} \sim 35^{o}$ $\theta_{23} \sim 45^{o}$ $\theta_{13} \sim ?$

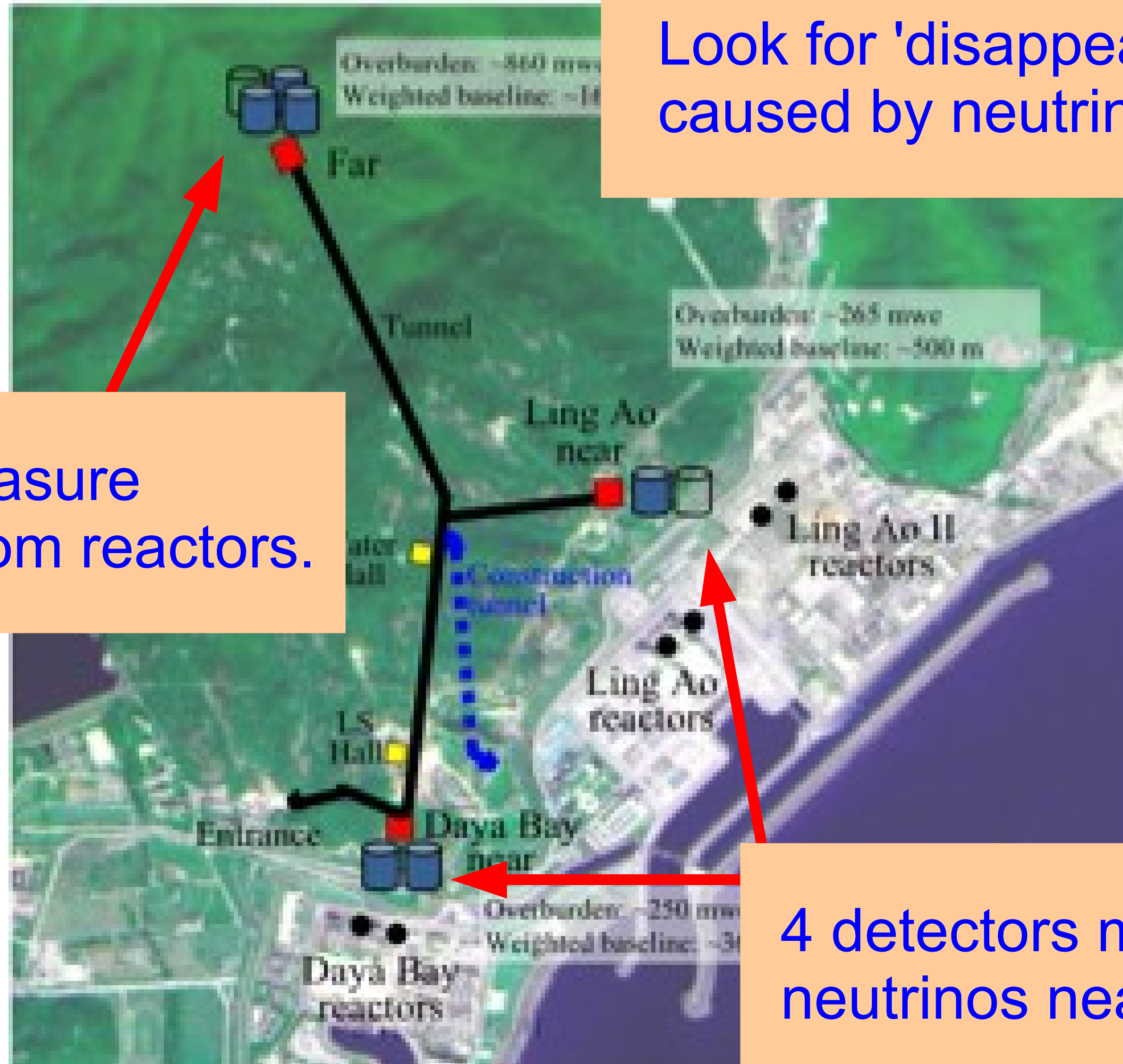
Nature chooses the values, we must measure by experiment.

Neutrino Hunting in China

Three Pairs of Nuclear Power Reactors → Lots of Neutrinos!

Nearby Mountains → Good place to stick a detector!

A Simple Plan...



Look for 'disappearance' caused by neutrino oscillation.

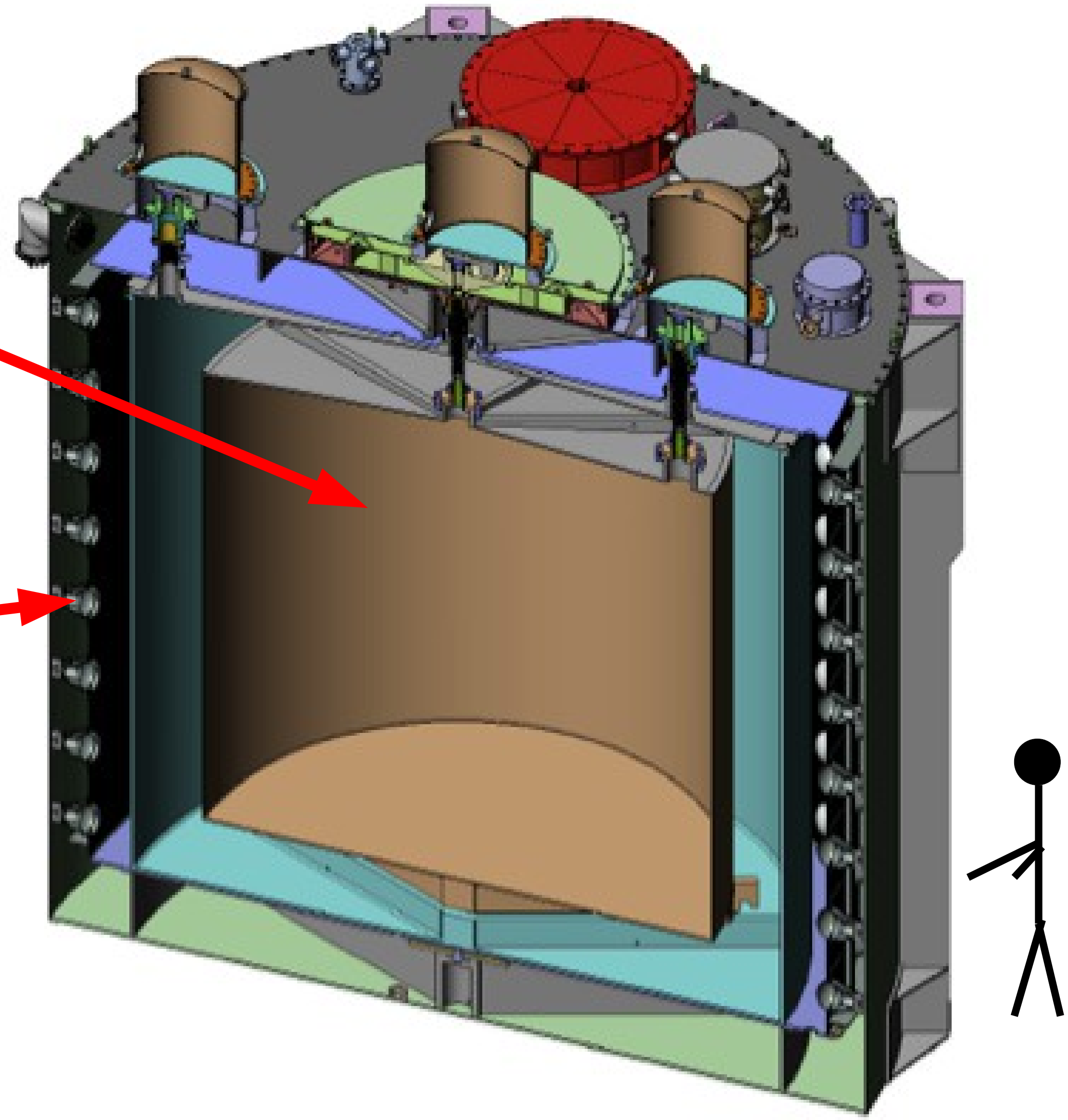
4 detectors measure neutrinos far from reactors.

4 detectors measure neutrinos near to reactors.

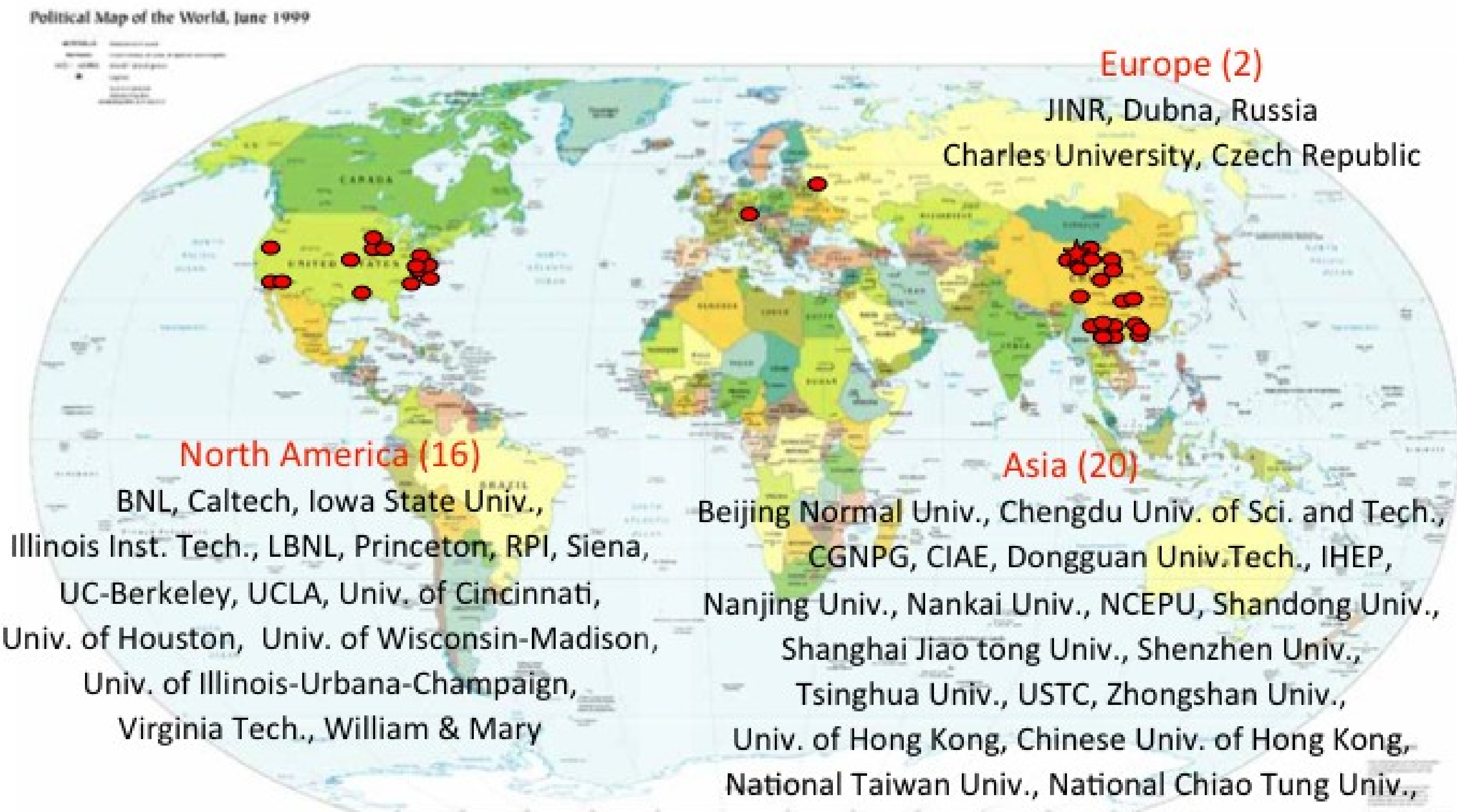
Bigger Target = More Neutrinos

20 tons of 'liquid scintillator' → neutrino target

~200 electric 'eyes' look for small flashes of light.



Daya Bay Collaboration



Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

North America (16)

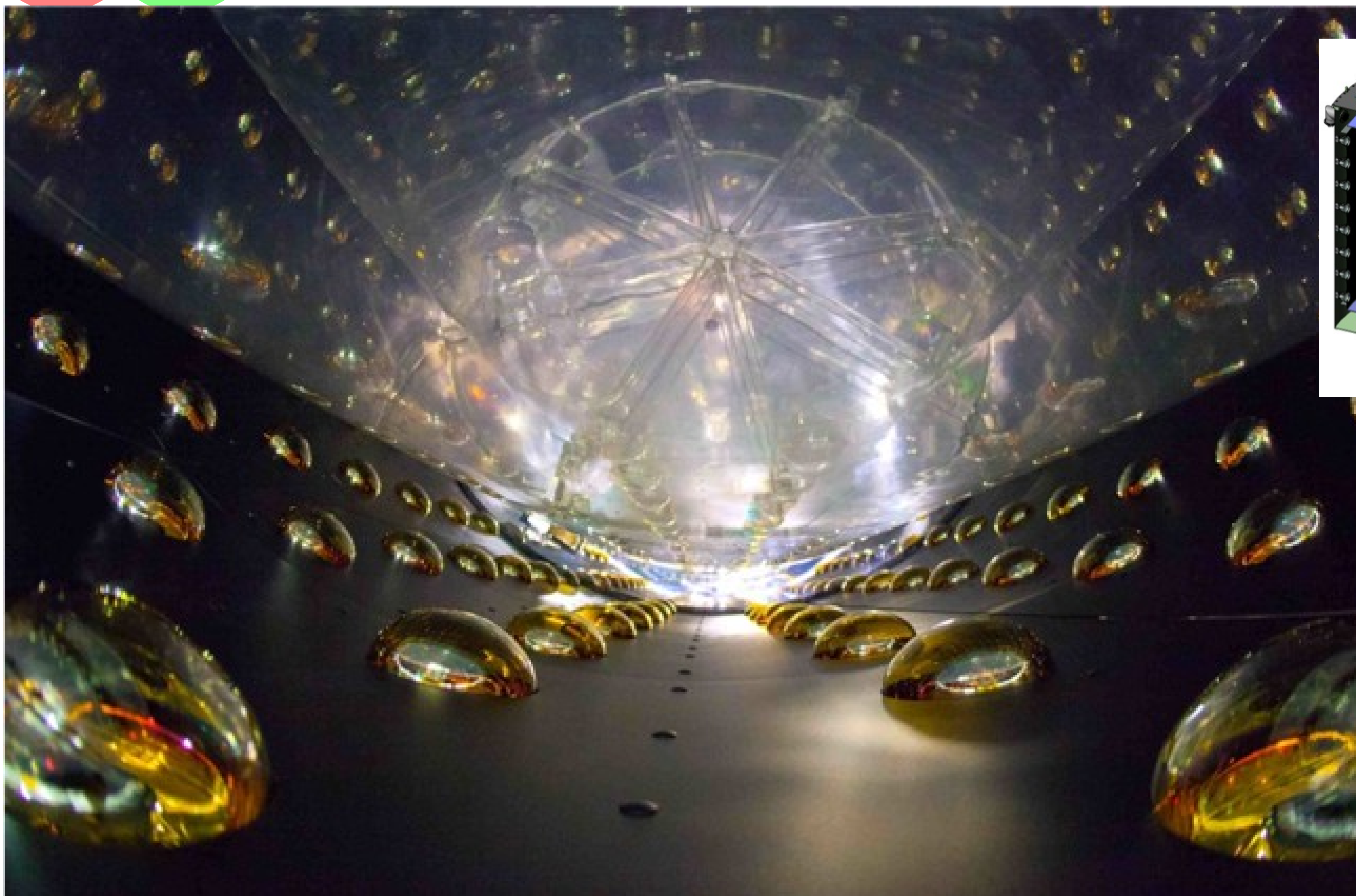
BNL, Caltech, Iowa State Univ., Illinois Inst. Tech., LBNL, Princeton, RPI, Siena, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin-Madison, Univ. of Illinois-Urbana-Champaign, Virginia Tech., William & Mary

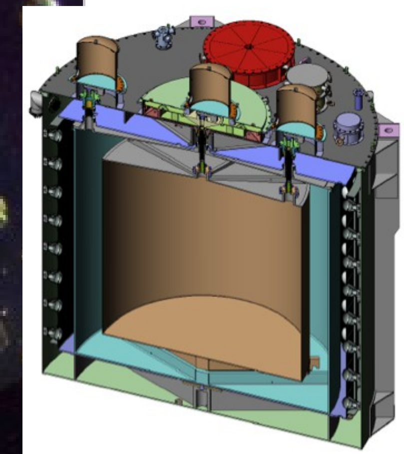
Asia (20)

Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Univ.Tech., IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

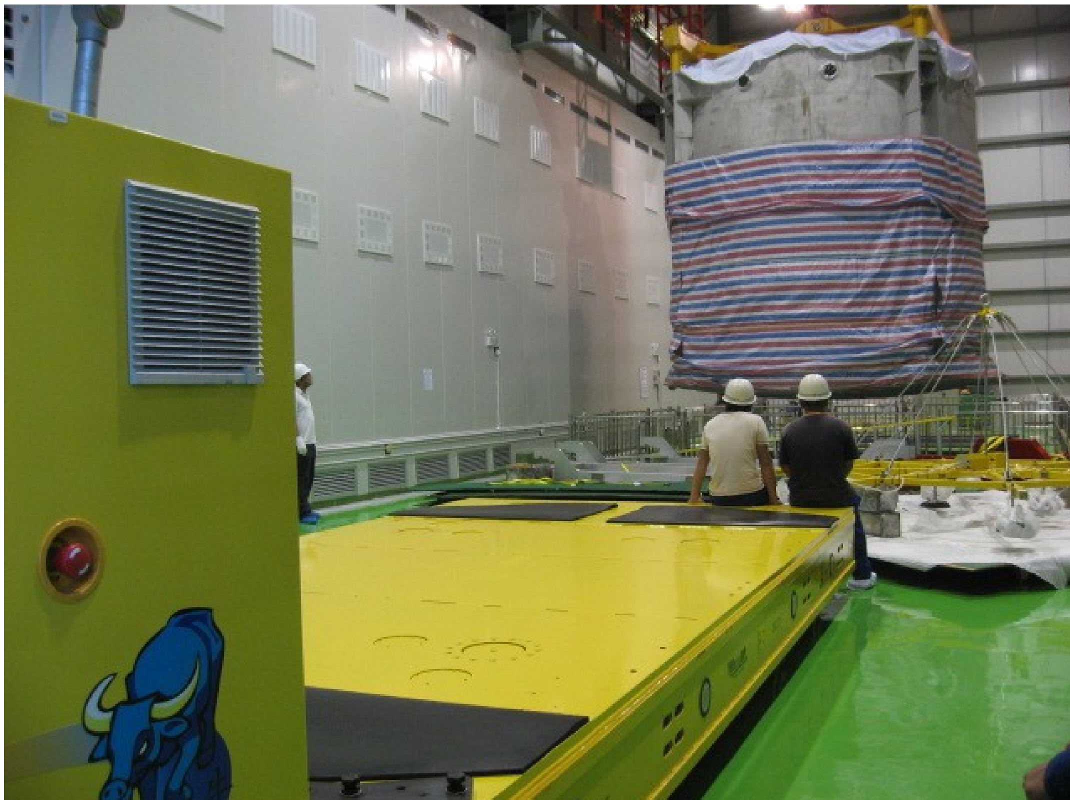
~230 Collaborators

From the inside





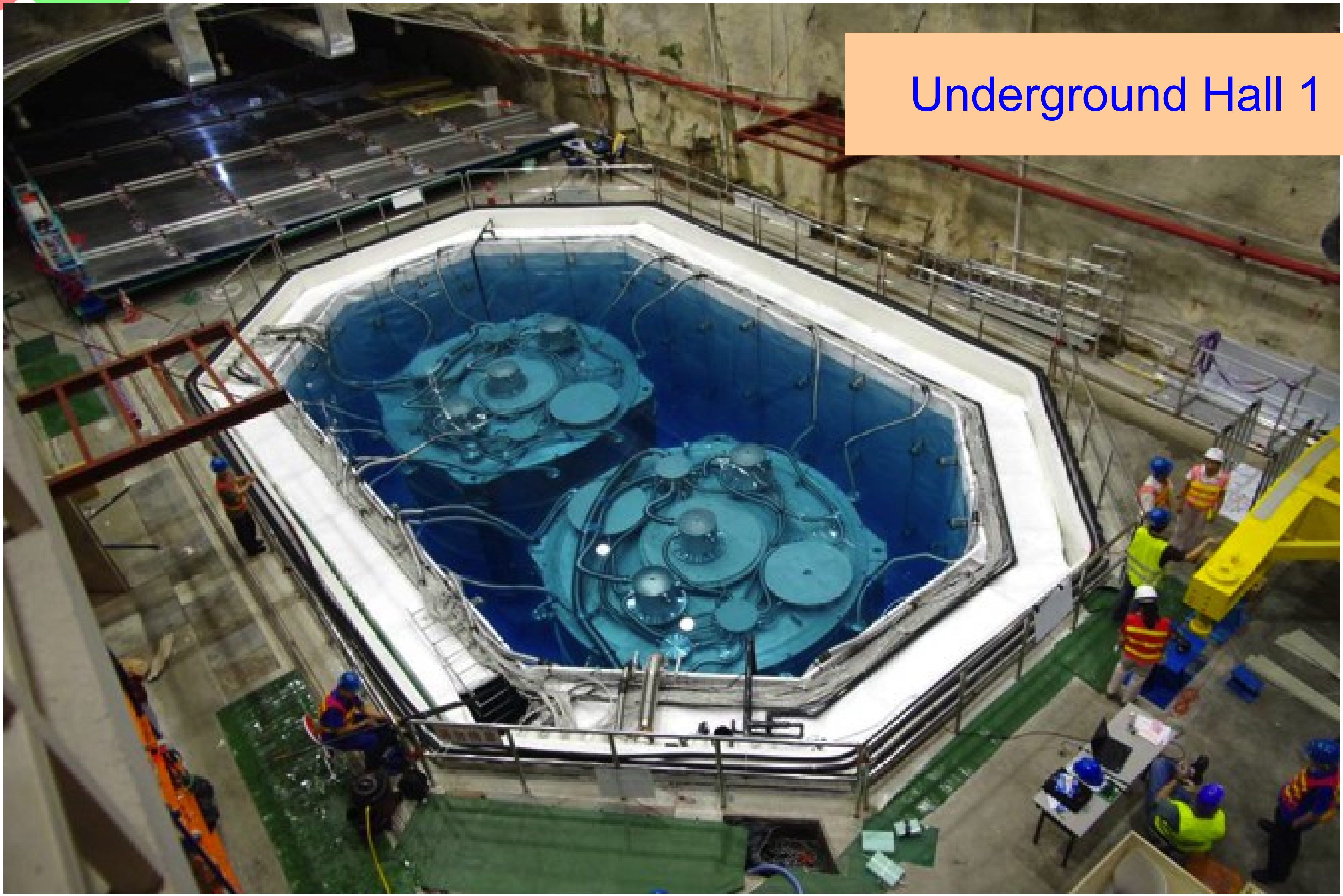
On the road



Lift detector out of assembly pit

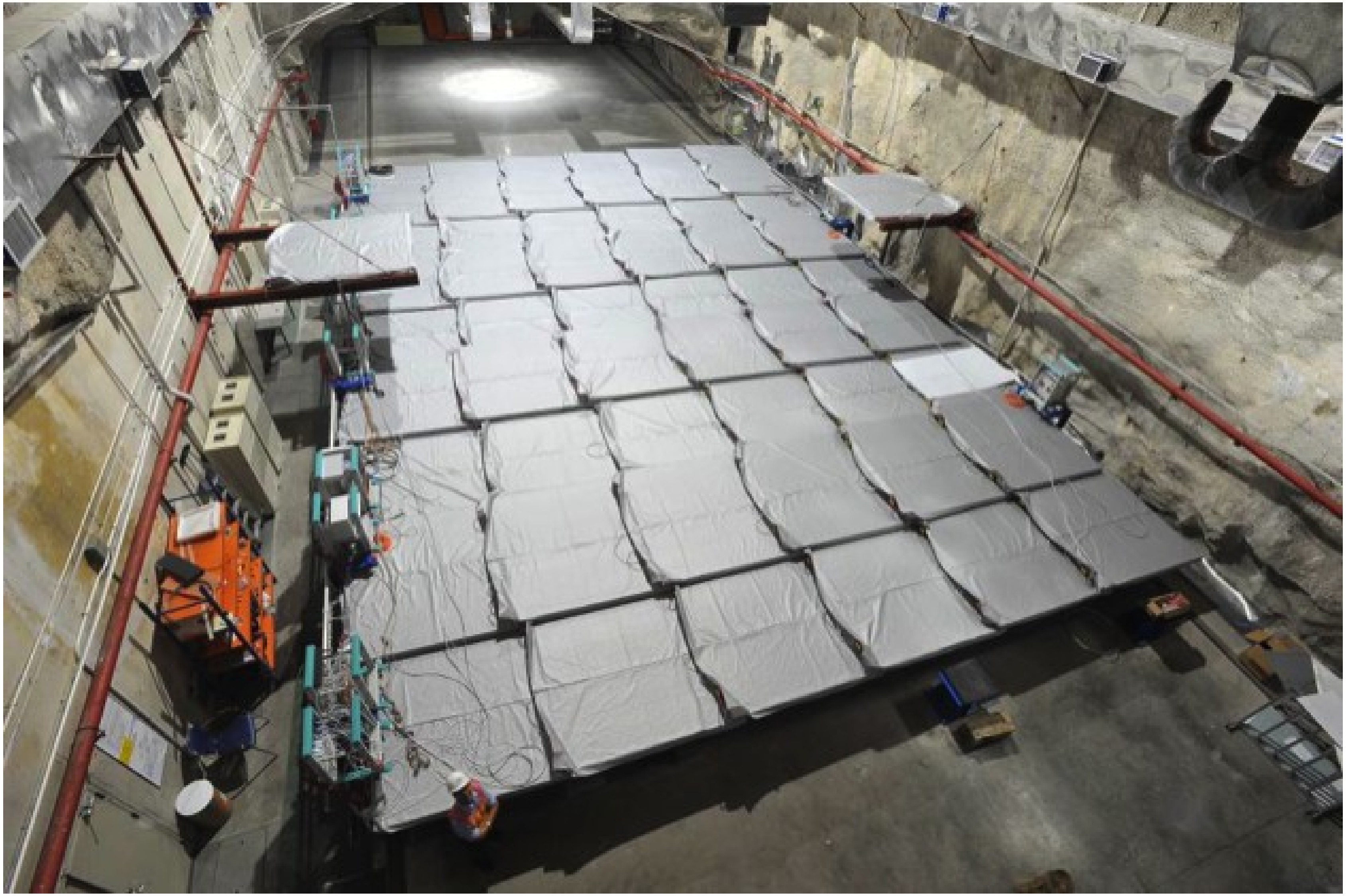
Transport into mine using specialized vehicle

Underwater



Underground Hall 1

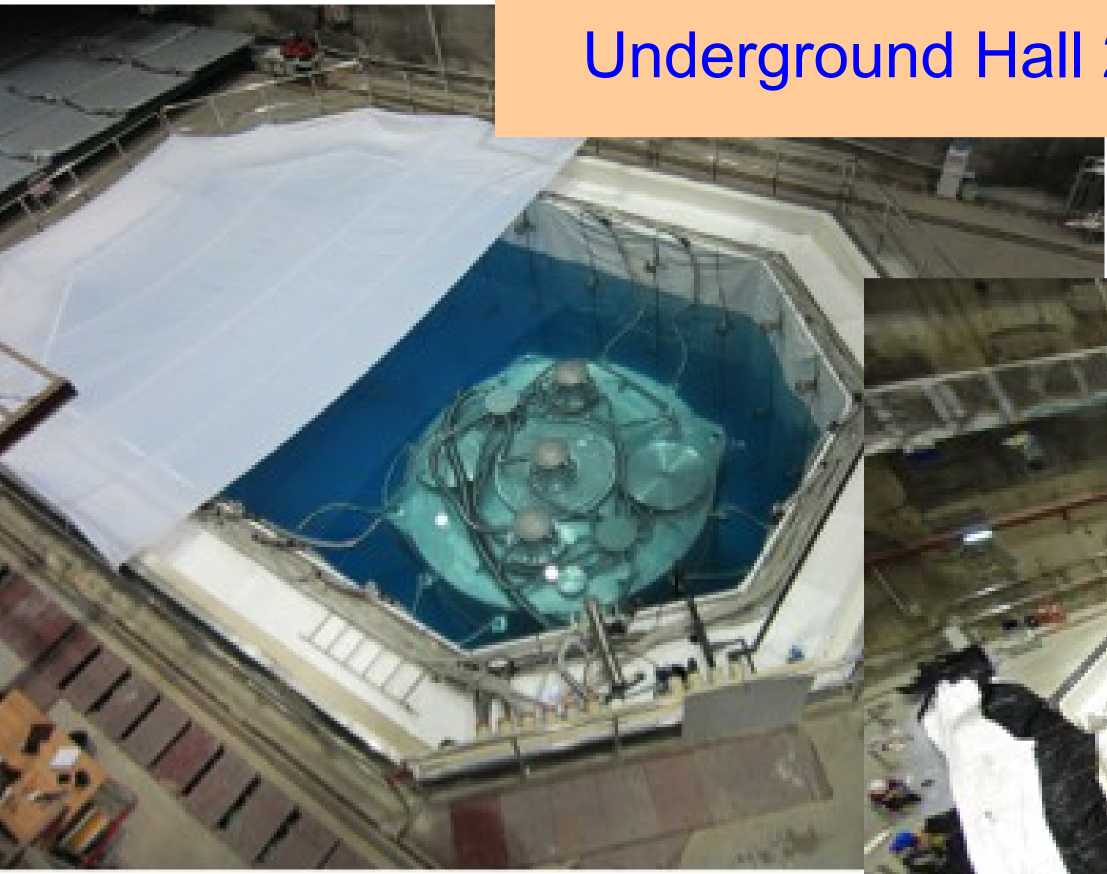
Ready to go...



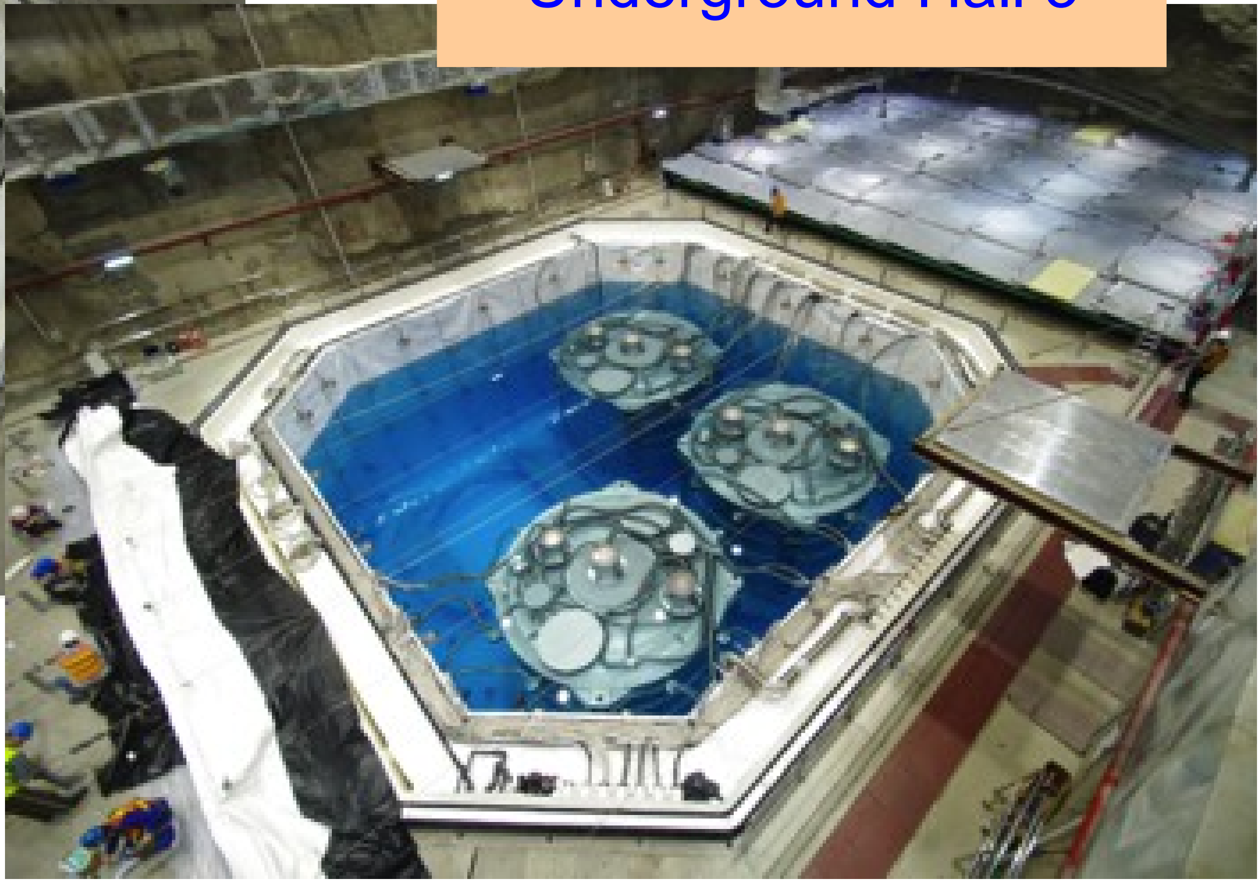
ν_1 ν_2 ν_3

Detectors everywhere

Underground Hall 2

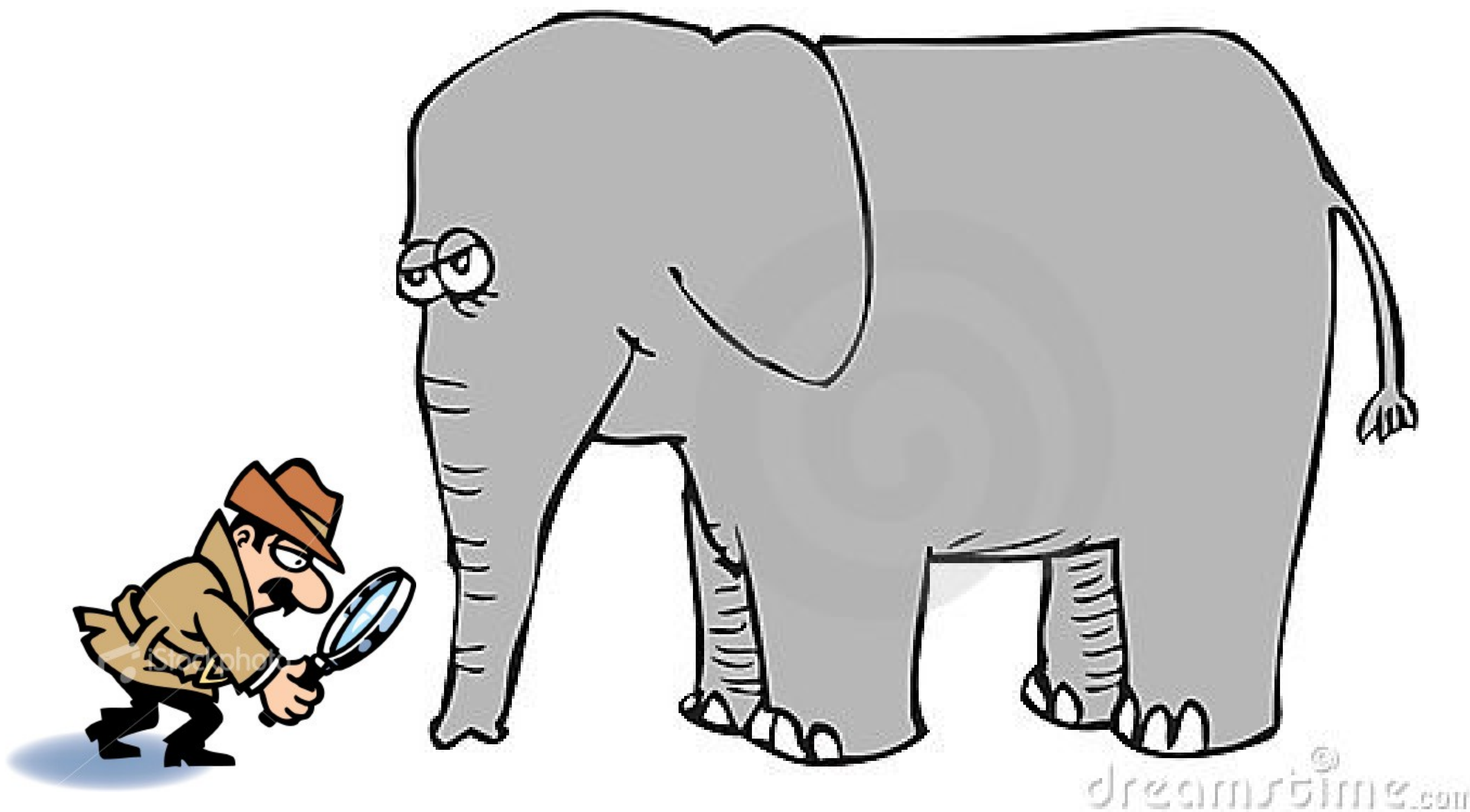


Underground Hall 3

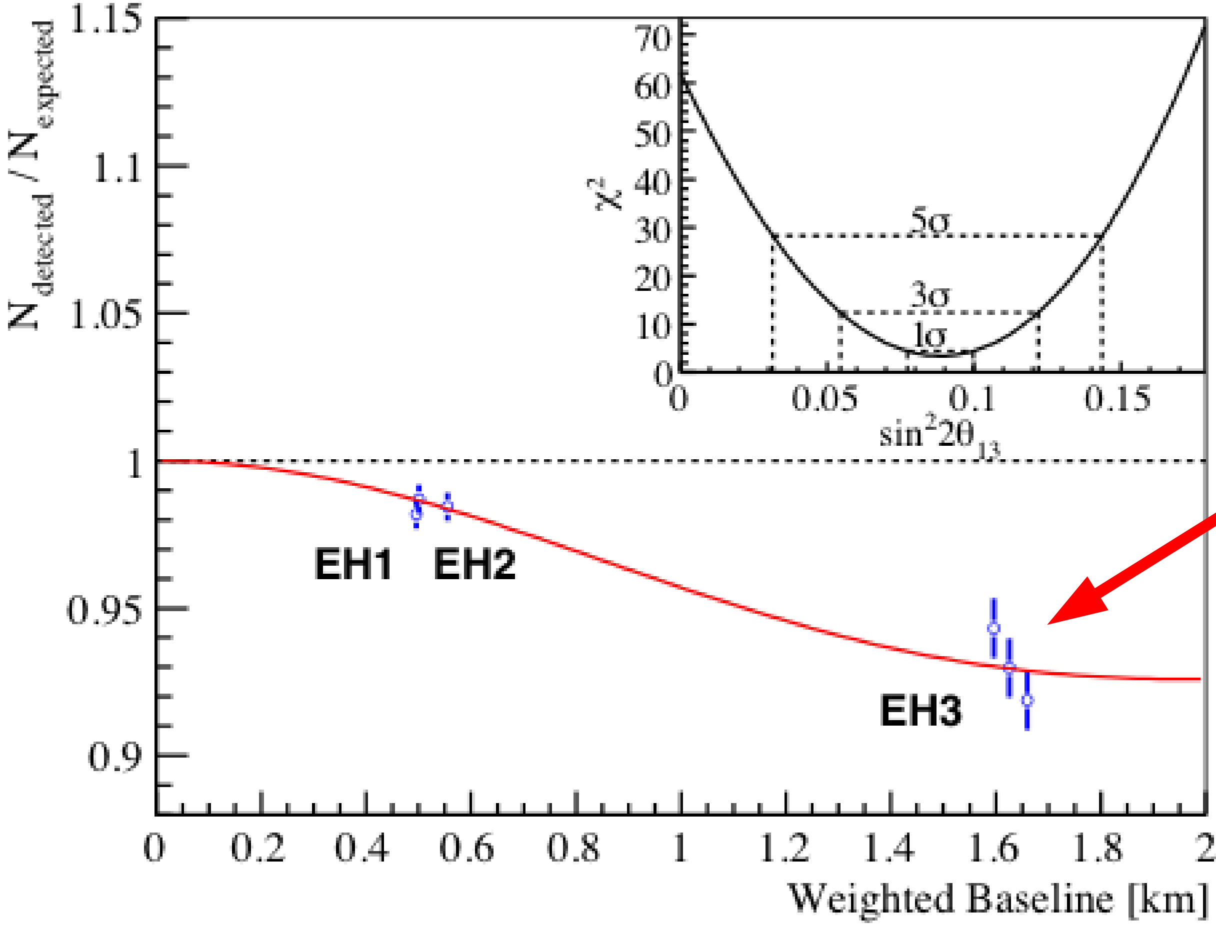


How small is θ_{13}?

How small is θ_{13}?



Obvious!



Far detectors see clear neutrino 'disappearance'!

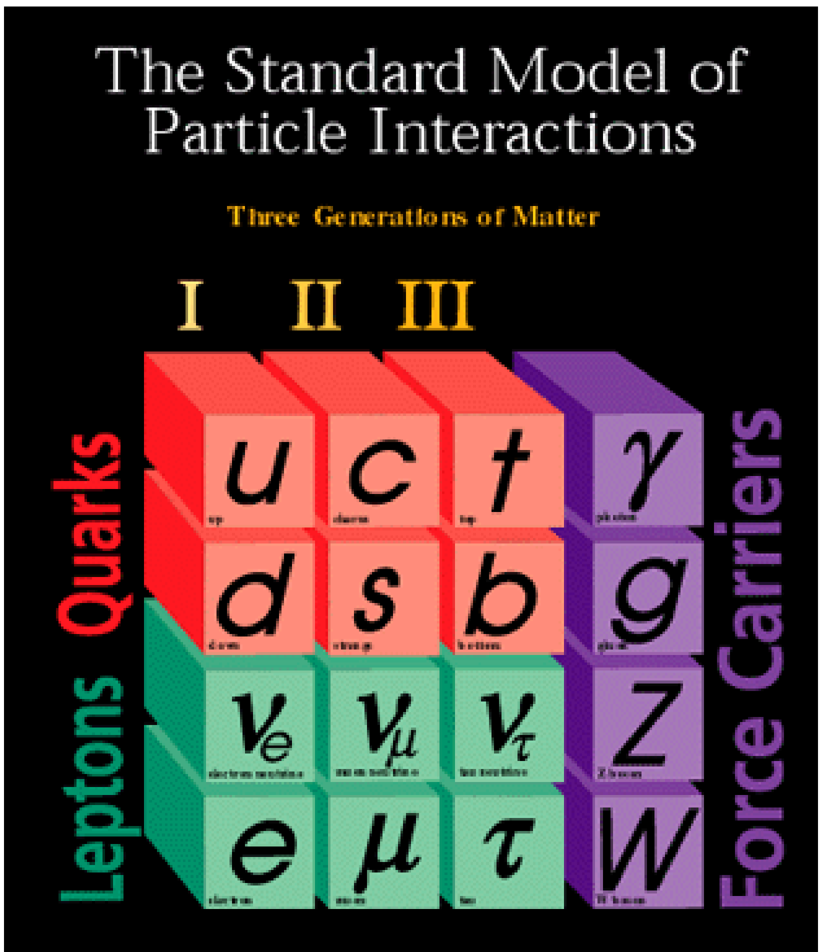
$\sin^2 2\theta_{13} = 0.089 \pm 0.010$ (stat) ± 0.005 (syst)

Act 4:
More trouble on the horizon...

Neutrinos oscillate...
so what?

Broken Laws...

Flavor is not conserved.



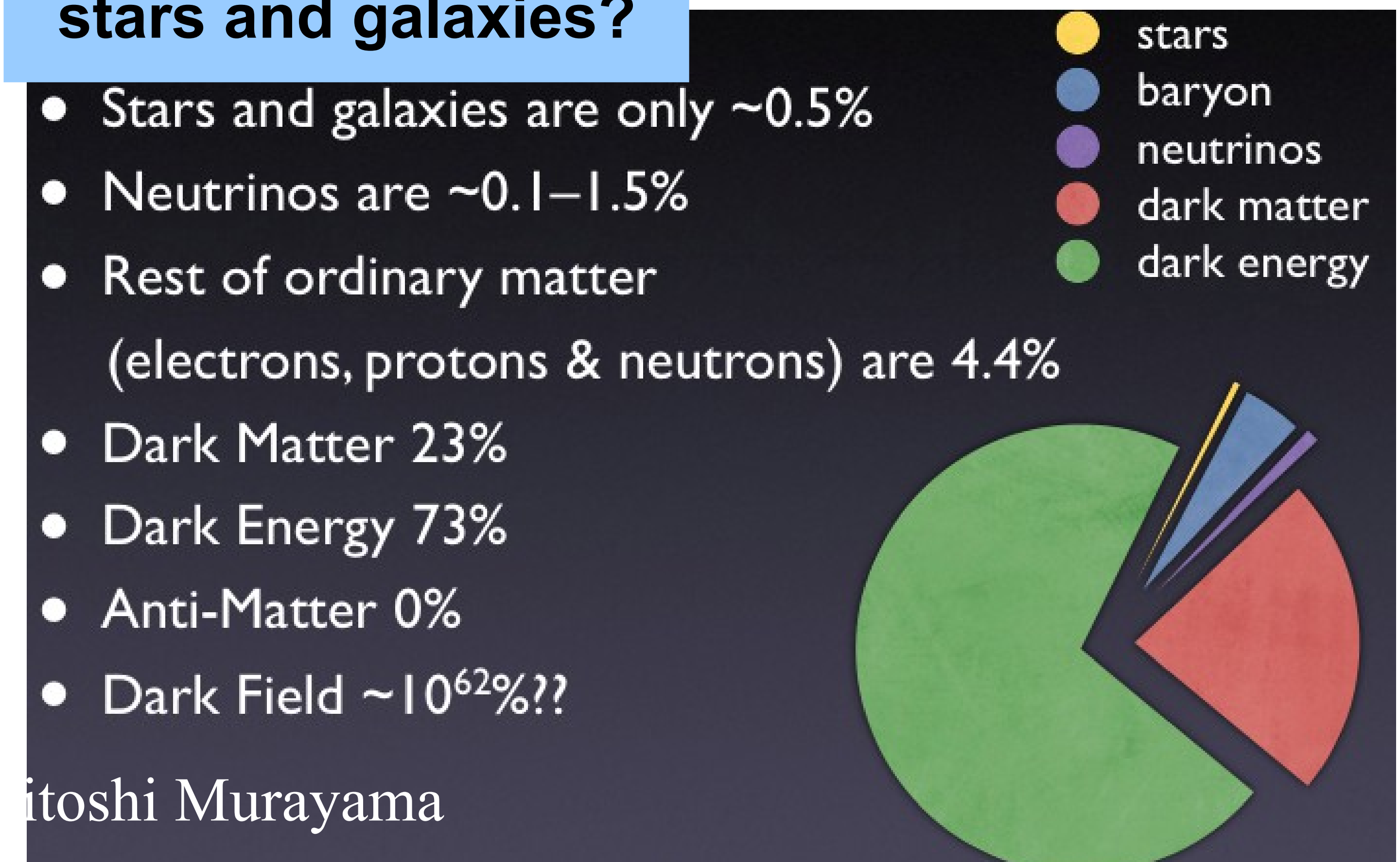
Number of electron, muon, tau particles can change...

… but sum is still conserved:

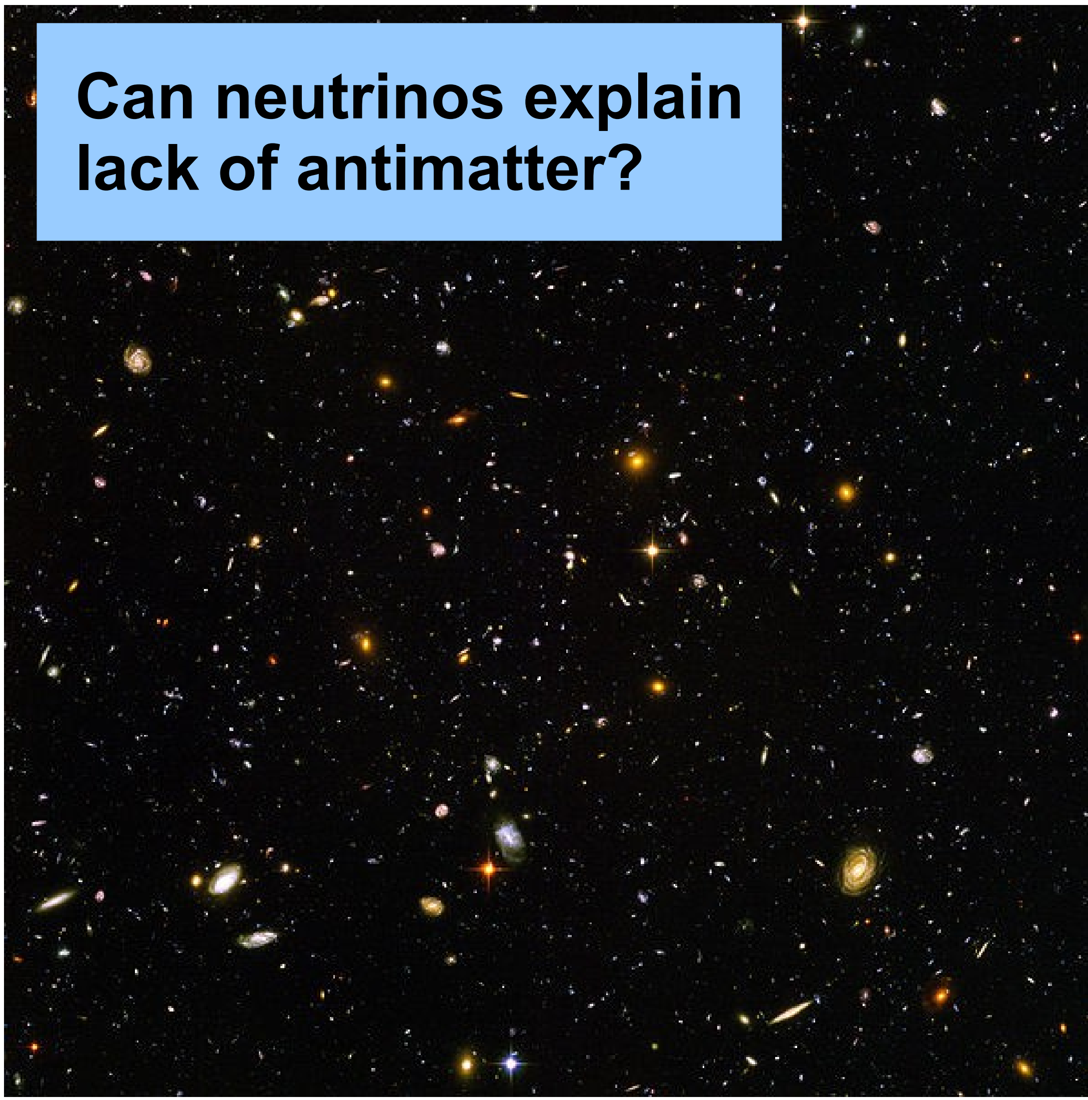
$$l_e + l_\mu + l_\tau = constant$$

Yes, they have mass...

More mass in neutrinos than all stars and galaxies?



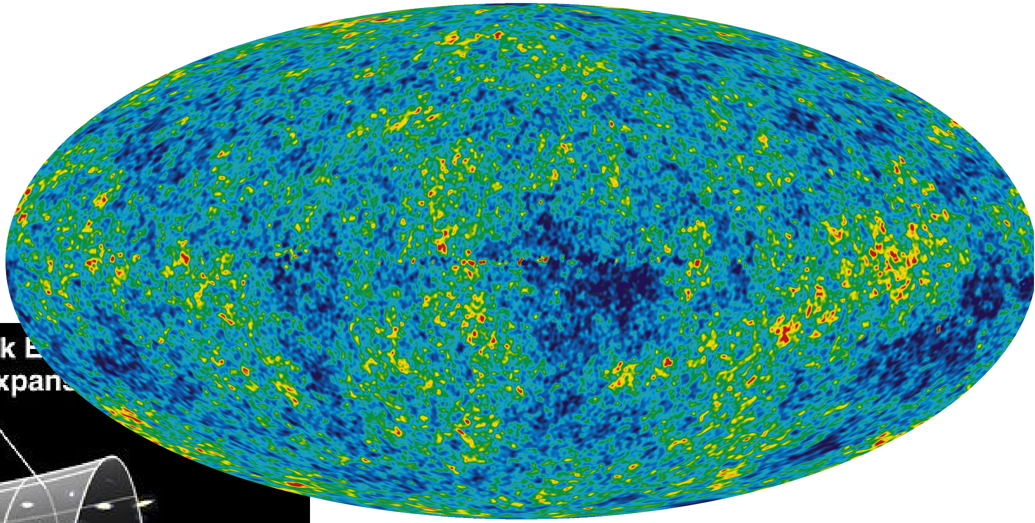
Balance Sheet Trouble

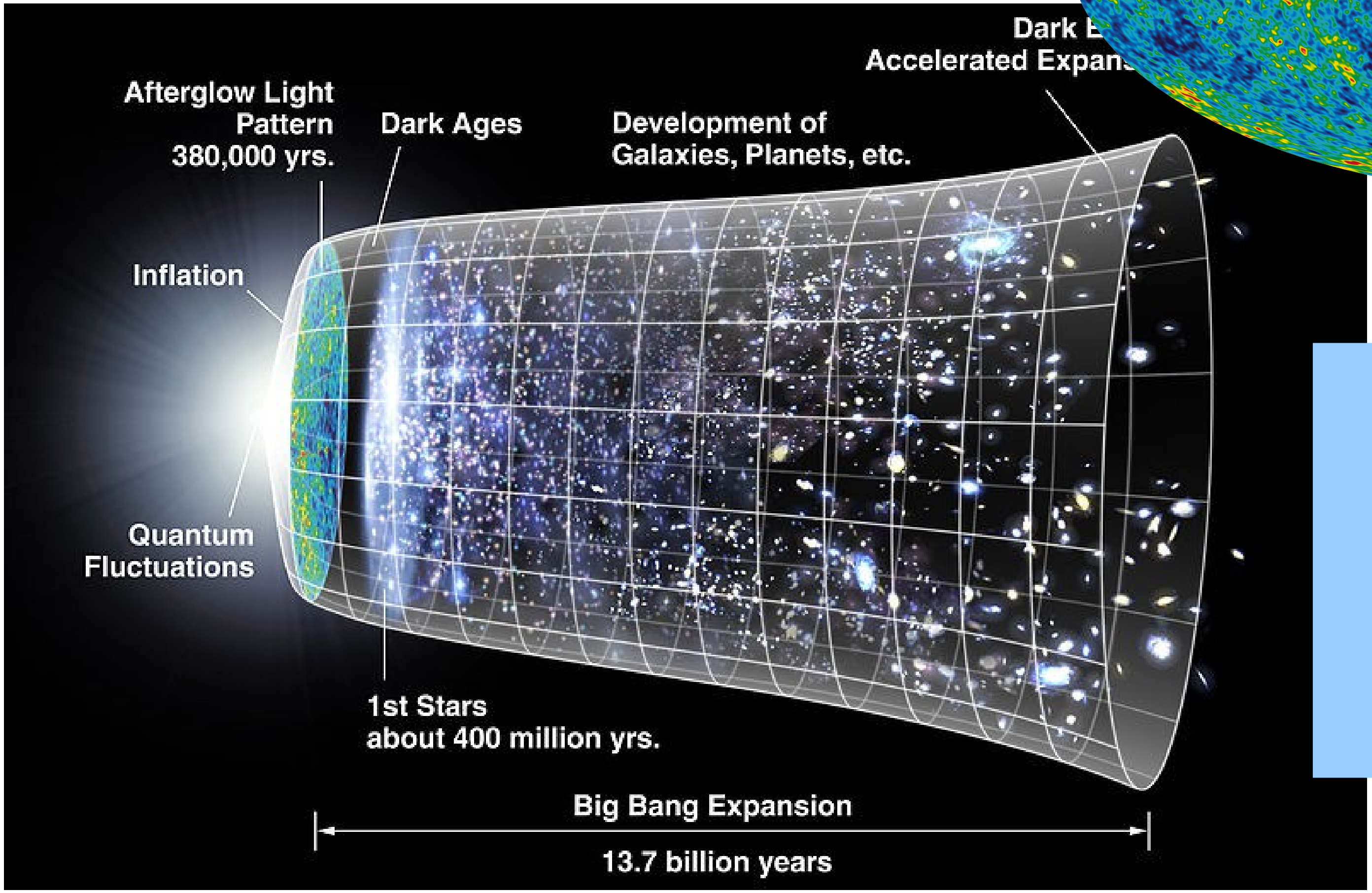


Can neutrinos explain lack of antimatter?

Try to measure by shooting neutrinos across the US.

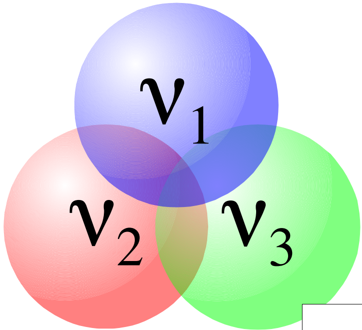
Big Bang Trouble



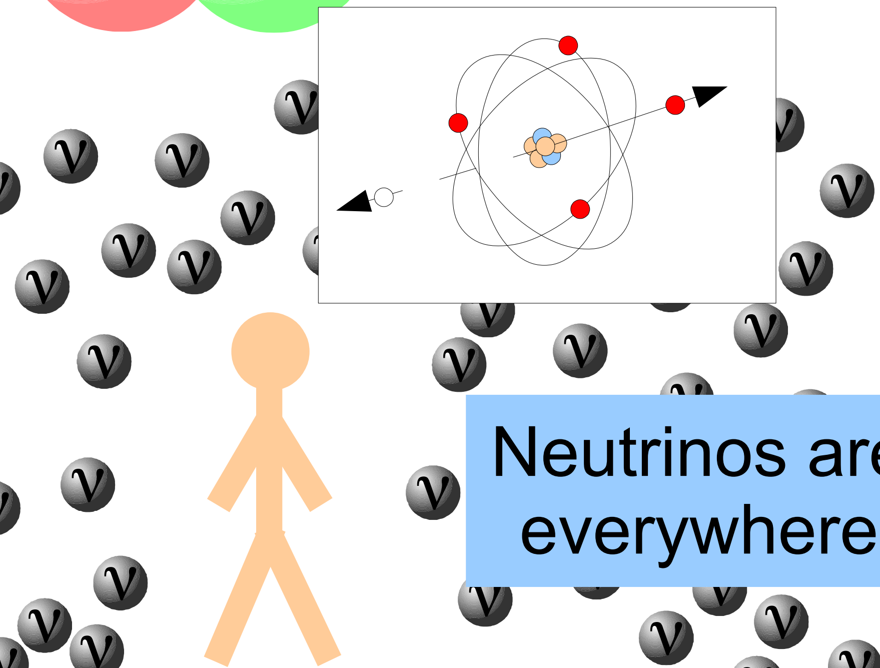


Challenge:

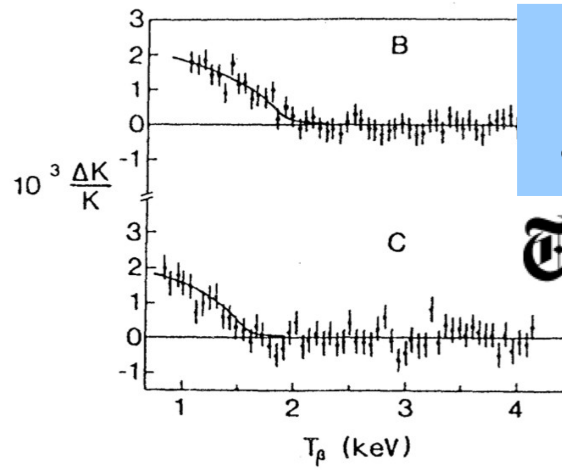
Can you measure the neutrinos from the Big Bang?



Parting Comments...

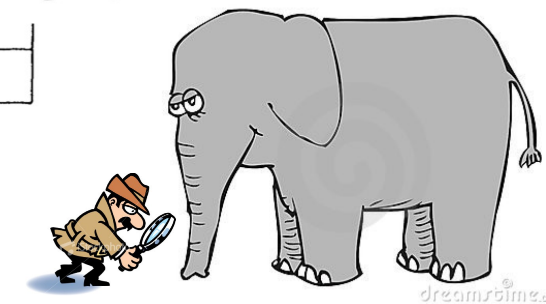


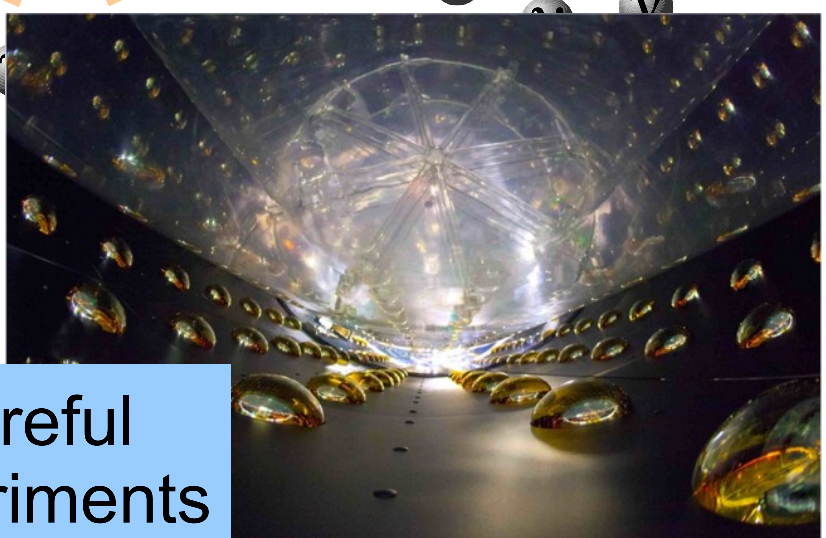
Neutrinos are everywhere



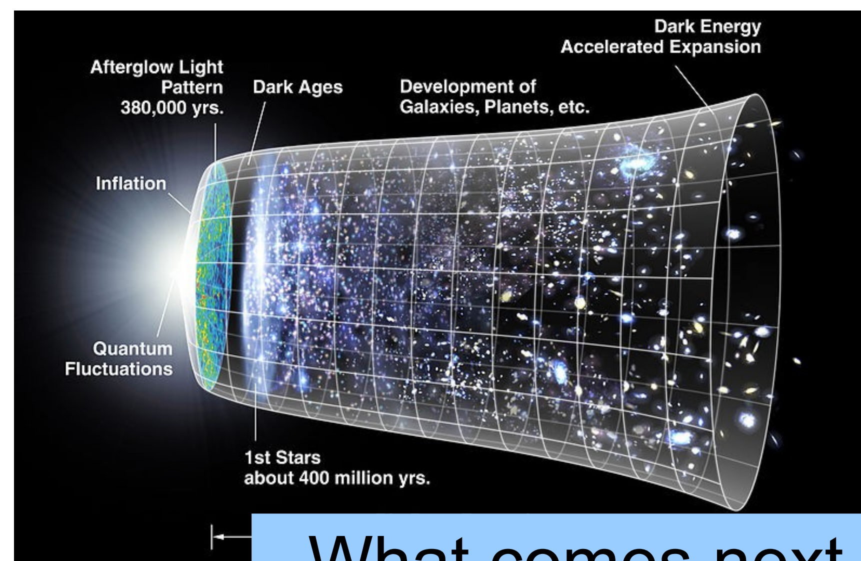
Neutrinos are not easy

The New York Times





Careful experiments



What comes next...